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Permeability Equipment for Porous Friction Surfaces

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(October 1984 to April 1985)

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16. Abstract

Hydroplaning is the loss of traction between tire and pavement due to the presence of a layer of water. This loss of traction can result in loss of vehicle control. A porous friction surface (PFS) applied over an existing pavement permits the water to drain laterally and vertically away from the tire path, effectively lowering hydroplaning potential. Equipment used to measure pavement drainage (permeability) is discussed with respect to usage on porous friction surface. Background information on hydroplaning, flow theory, and PFS field performance as they are affected by permeability are also presented.

Pavement permeability equipment is divided into two groups: static test devices and dynamic test devices. Static test devices measure pavement permeability up to the hydrodynamic pressure range. Dynamic test devices measure pavement permeability in the hydrodynamic pressure range. Two dynamic test devices and four static devices are considered for measuring PFS permeability.

Permeability tests are recommended to measure PFS permeability for maintenance purposes and construction control. Dynamic devices cited in this report could possibly estimate hydroplaning potential; further research must be done to determine this. Permeability devices cannot be used to accurately estimate friction of a pavement surface, however, decreased permeability of a pavement infers a decrease in friction. A static test device, which has been extensively field tested by the U.S. Army Engineer Waterways Experiment Station (WES), is recommended to measure PFS permeability.

17. Key Words
Pavement Texture
Hydrodynamic Pressure
Porous Friction Surface (PFS)
Dynamic Test Devices
Pavement Permeability
Static Test Devices

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METRIC CONVERSION FACTORS

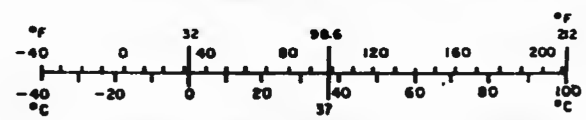
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



SECTION I
INTRODUCTION

OBJECTIVE

The main objective of this report is to identify permeability measurement devices currently in use or adaptable for measuring the ability of a Porous Friction Surface (PFS) to drain. This report was written to assist in selecting a permeability device for use on airfield PFS pavements.

BACKGROUND

The loss of friction because of inadequate bulk water drainage from runway surfaces is a worldwide problem. Common runway pavements which provide the most adequate bulk water drainage can be grouped into the following types:

1. Grooved Portland Cement Concrete (GPCC)
   0.25- x 0.25- x 1.5-inch (6.4- x 6.4- x 38.1 mm) transverse saw-cut grooves.
   Grooves are cut in cured concrete pavement; these grooves provide water drainage.
2. Plastic Grooved Portland Cement Concrete (PGPCC)
   Grooves are made with a heavy rake while concrete is in the plastic or uncured state.
3. Grooved Asphalt Cement Concrete (GAC)
   Dense asphalt pavement; grooves made by saw-cut or reflexive--percussive method.
4. Porous Friction Surface (PFS), also known by such names as popcorn mix, open-graded mix, porous friction course, and plant mix seal. PFS is an open-graded overlay placed on an existing pavement in a thin layer, optimally 0.75- to 1.00-inch (19- to 25 mm) thick, to increase the surface texture and improve water drainage.

Of these pavement types, PFS compares favorably as a solution for inadequate drainage and surface texture. Pavement permeability and texture are the most important physical features of PFS with respect to aircraft runway friction. Several variables affect the bulk water removal or permeability of PFS. Accurate measurement of PFS permeability can be used to recognize variables affecting permeability values and also aid in correcting problems during design, construction, and maintenance of PFS pavements.

SCOPE

This report discusses PFS permeability, its effect on runway operations, the principle variables affecting PFS permeability, and the devices used to measure it. Related information is also presented which establishes the dependency of friction and hydroplaning on pavement drainage; flow through porous media theory is discussed in relation to permeability testing techniques; and a discussion on PFS performance emphasizes the need for porous friction surface permeability testing.

SECTION II
FRICTION AND HYDROPLANING

The development of friction between an aircraft tire and pavement surface is a complex phenomenon. The theory relating the interaction of the tire and pavement structure is not simple. Factors such as the influences of rain (wet surface), aircraft dynamics, variable pavement surfaces, and pilot operational technique present a theoretical problem that has become a lifetime study of many researchers in the aerospace and pavements industry.

Yager (Reference 1) discusses the principal factors of weather, aircraft, runway, and pilot technique which combine to affect aircraft ground-handling performance during wet runway operations. These components are shown in flow-chart form in Figure 1.

Figure 1 shows that atmospheric conditions and runway geometry control the runway water depth. Aircraft tire design, inflation pressure, and ground velocity coupled with the texture characteristics of the pavement surface are shown to control the tire-pavement drainage capability. The water depth and drainage capability govern the amount of tire-pavement friction available. Yager does not specifically mention pavement permeability as a factor, however, PFS macrotexture has been shown to provide drainage channels between the tire and pavement. These channels increase the tire-pavement drainage capability while decreasing the runway water depth. The influence of aircraft design and pilot input are also known to influence the performance of an aircraft on wet runways.

In reviewing the factors which influence aircraft runway performance, Reference 1 states that several approaches are needed to alleviate the severity of the problem. These include continued pilot education and training, implementation of procedures for monitoring slippery runway conditions, implementation of procedures for notifying pilots when severe runway conditions exist, improvement of antiskid brake system performance, and prompt remedial treatment of runway surface drainage problems. The quality of the pavement, from a surface texture standpoint, must also be ensured at the design, construction (quality control), and maintenance levels during the life of the pavement.

TIRE-PAVEMENT FRICTION THEORY

As previously stated, the theory of tire-pavement interaction with regard to friction is quite involved. A number of major works have been written on the subject of tire-pavement friction. The most notable theoretical discussions on this subject are by Moore (Reference 2) and Kummer (Reference 3). While these authors emphasize the importance of tire and rubber design in friction development, they also note the importance of pavement surface texture, particularly macrotexture and microtexture.

Reference 2 differentiates macrotexture from microtexture as follows. The individual asperities or stones in a pavement surface constitute the macrotexture, while the finer asperities (or grit) on the larger asperities constitute the microtexture. Figure 2 illustrates the difference between macrotexture and microtexture. According to Reference 3, typical wavelengths (λ) associated with macrotexture are 6 to 20 mm (0.25 to 0.80 inch), and for microtexture 10 to 100 μm (0.0004 to 0.004 inch).

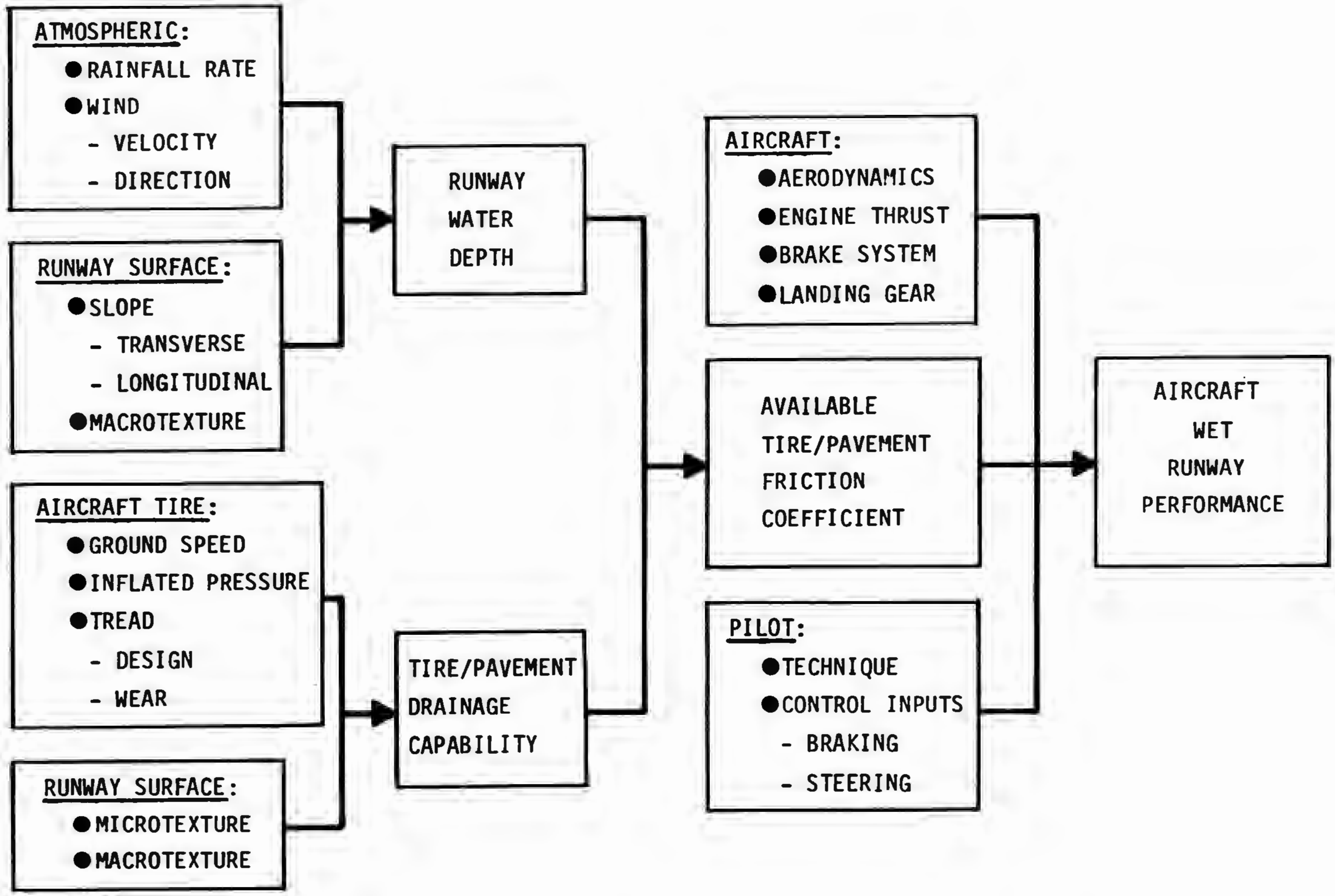


FIGURE 1. FACTORS AFFECTING AIRCRAFT WET RUNWAY PERFORMANCE (REFERENCE 1)

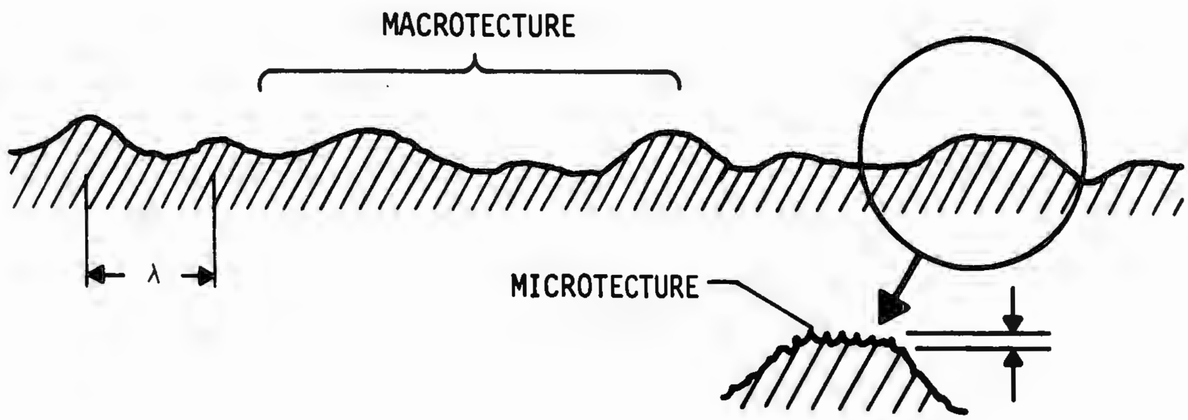


FIGURE 2. PAVEMENT ROUGHNESS INDICATING MACROTEXTURE AND MICROTEXTURE (REFERENCE 2)

Good pavement macrotexture provides drainage channels between the tire and pavement surface. These channels promote quick removal of bulk water, decreasing the likelihood of producing water depths necessary for dynamic hydroplaning to occur (Reference 4). Good microtexture penetrates the thin water-film coating of wet pavement to maintain dry contact between the tire and pavement.

HYDROPLANING THEORY

A general definition of hydroplaning is the loss of traction between tire and pavement due to the presence of a layer of water. Browne (Reference 5), in discussing pneumatic tire hydroplaning, states there are three types of hydroplaning; dynamic, viscous, and reverted tire rubber.

Dynamic hydroplaning occurs when the amount of water encountered by the tire exceeds the combined drainage capacity of the tire tread pattern and the pavement macrotexture. It occurs in deep fluid layers where fluid inertial effects predominate. The pressure on the tire surface increases with increasing tire speed until it is greater than the internal tire pressure, which results in a complete separation of tire from pavement. It is known that the dynamic hydroplane velocity is proportional to the square root of the tire pressure. Horne and Joyner (Reference 6) found that

$$V_H = 1.8\sqrt{P_{IN}} \tag{1}$$

where V_H is in meters per second (m/s) and P_{IN} is the tire inflation pressure in kilopascals (kPa).

Viscous hydroplaning occurs predominately on surfaces with little microtexture. This lack of microtexture promotes a thin water film between tire and pavement. This type of hydroplaning can occur at any speed and at any fluid depth. The tire pressure determines whether viscous hydroplaning will persist at moderate or high speed; the greater the inflation pressure, the more likely viscous hydroplaning will develop rather than dynamic hydroplaning.

Reverted tire rubber hydroplaning occurs when large aircraft lock their wheels (or spin up at touchdown) when moving at high speeds on wet pavement with adequate macrotexture but little microtexture. Heat buildup at the tire-pavement interface from sliding causes the rubber to melt. The tire then slides on a film of molten rubber, water, and steam.

A more elaborate discussion of the tire-pavement interaction mechanism during hydroplaning is presented by Moore (Reference 7). Moore considers the case of a tire rolling on a wet surface at speeds below the hydroplaning limit (or velocity). Hydroplaning upward thrust exists in the wedge just ahead of the tire contact area. The magnitude of this thrust is dependent on factors such as; effective tread width, water layer depth, tire inflation pressure, vehicle velocity, and pavement surface texture.

Sufficient drainage through a porous surface such as PFS can impede or prevent dynamic hydroplaning. Bulk water drainage delays, to much higher speeds, fluid dynamic pressure buildup which causes dynamic hydroplaning. Flow of fluid through porous media is essential to bulk water removal. Several theories and modeling techniques have been used to describe the phenomenon of flow through a porous media.

SECTION III
THEORY OF FLOW THROUGH POROUS MEDIA

The most common theory of flow through a porous media is Darcy's law. Based on an experiment in 1856, a relationship was discovered between flow, area, and decreases in hydraulic pressure. Simply stated, Darcy's law is

$$Q = KiA \tag{2}$$

where

Q = volumetric flow (L^3/T)
K = a permeability constant dependent on physical properties of both the fluid and the medium tested (L/T)
i = a hydraulic pressure gradient ($\Delta P/\Delta X$); change in pressure is expressed in height of water divided by sample length (L/L)
A = cross-sectional area of sample (L^2)
L = length
T = time

To increase its applicability, Darcy's law is expressed in differential form:

$$q = - \frac{k}{\mu} \gamma \, \mathrm{grad}(p) \tag{3}$$

where

$k/u = K$
k = is specific permeability constant of media without effects of fluid (L^2)
μ = absolute viscosity of fluid ($M \cdot T/L^2$)
q = volumetric flow per unit area or seepage velocity (L/T)
$\mathrm{grad}(p)$ = hydraulic pressure gradient (L/L)
γ = specific weight (M/L^3)

Darcy's law is only valid for laminar flow of a fluid. Compounding this inadequacy, the transition from laminar flow to turbulent flow in a porous medium occurs at a very low Reynolds number. This critical Reynolds number ranges between 0.1 and 75 (Reference 8). For example, a sand with a porosity (ratio of volume of voids to the total volume) of 19.7 percent becomes turbulent at a Reynolds number of less than 0.5 (Reference 9). Since Darcy's law is only valid in a limited range of flow conditions, researchers have sought to generalize it by various empirical and analytical techniques. Reference 9 cites a number of such techniques, however, such techniques proved unsuccessful for extending Darcy's law to the turbulent flow regime.

Another limitation of Darcy's law is that the permeability constant must be determined experimentally. For this reason, attempts have been made to determine the value K analytically by considering the geometry of the medium.

Geometric representations of the medium have included the following:

1. Straight Capillaric Models
2. Parallel Capillaric Models
3. Serial Capillaric Models
4. Hydraulic Radius Theories
5. Kozeny Theory
6. Drag Theories
7. Statistical Theories

All of the above theories are modifications of Darcy's law and are discussed in detail in Reference 8. Each of these theories helps explain partially the complexities of Darcy's permeability constant K, yet none proved to be a substitute for the experimentally derived coefficient of permeability K.

Therefore, when using the permeability constant as criteria for either design or maintenance, care must be taken to ensure that the value used is correctly measured and applied.

DIRECT WATER AND AIR PERMEABILITY MEASUREMENTS

Most water and air permeability measurement techniques found in this literature search expressed permeability as flow rates. Expressing permeability in this way is not a strictly valid expression of Darcy's law; yet, when dealing with field testing of pavements, neither the cross-sectional area of flow nor the hydraulic pressure gradient can be directly measured; therefore, permeability cannot be computed. In one study, permeability measurements from variable and constant head tests were expressed as "time to fall" and "flow rate" respectively. Using these values, the coefficients of permeability K(cm/s) were computed using equations relating flow path, area, head, and time. These equations are derived in Reference 10. Expressing permeability directly as a flowrate is much less complex. For this reason, many researchers have adopted the use of flow rates to compare pavement drainage characteristics. The measured flow rates can be classified into one of three groups:

1. Flow through the surface channels formed by the pavement's macrotexture.
2. Flow through the porous pavement itself.
3. Combined flow through both the surface channels and the porous pavement.

Methods have been devised to measure both the combined flow and the flow through porous pavement. To measure the combined surface flow and porous flow, rubber gaskets simulating the draping and sealing characteristics of tires are used. This sealing condition measures combined flow. To separate the effect of pavement texture from the porous pavement, grease or commercial sealants are used between the pavement and measuring device. These devices use two fluids, air and water, in two test modes, static or dynamic. Static devices are used for ease of setup and repeatability of results. These methods do not simulate flow conditions under a moving tire; however, they eliminate variance due to compressibility of fluid, combined turbulent and laminar flow regimes, high load seating requirements, and transient pressure gradients. Dynamic test methods are used to simulate actual operating conditions. These methods require highly skilled personnel, since test results depend on close control of setup and operating conditions.

SECTION IV
PERMEABILITY OF POROUS FRICTION SURFACES (PFS)

In the United States, PFS pavements have mainly been used for highway pavement surfacing. PFS airport pavements have been constructed in the United States, but the most frequent use of PFS airport pavements has occurred in Western Europe and England. PFS is a free-draining, open-graded overlay that can be placed on a pavement in a thin layer, optimally 19 to 25 mm (0.75 to 1 inch). PFS is used to increase the texture and improve the drainage of an existing pavement.

The basic differences in design, construction, and performance requirements for PFS are traffic loadings. In highway pavements, the traffic characteristics are high density, light loads, and low tire pressures [maximum 690 kPa (100 $lb/in.^2$)]. Airport and military PFS pavements must perform under relatively low density and heavy load conditions with high tire pressures [maximum 2758 kPa (400 $lb/in.^2$)]. PFS pavements for highways are sometimes designed for high traffic density and, in other applications, for high permeability. Most airport PFS pavements are designed with high permeability for internal drainage of water through the mixture.

EFFECT OF CONTAMINANTS

Contaminants on PFS pavement can affect its permeability. Sand spread on PFS runways during icy conditions has shown no adverse affect on permeability of the pavement. Jet engine exhaust and wind usually remove the sand before it has an opportunity to fill the pavement voids (Reference 11). The buildup of debris in voids has led to eventual clogging with a loss of permeability in highway PFS pavement (Reference 12). In another study of highway pavements, PFS test sections retained permeability (Reference 13). The difference appears to be in mix designs, construction controls, and pavement base conditions.

Jet fuel, hydraulic oil, and chlorobromomethane (used in firefighting) will dissolve the asphalt binder used in PFS. Delamination can result, causing a serious runway debris problem. However, new PFS pavements resistant to fuel and chemical spills are being developed (Reference 11).

Rubber buildup, resulting from aircraft operations, has a detrimental affect on permeability, which results in poor internal drainage. Loss of friction and increased hydroplaning potential are a direct result of poor drainage during wet runway operations (Reference 14). Observation of Air Force Base PFS pavements seems to indicate that less rubber buildup occurs on PFS than on conventional pavements (Reference 15). Various major airports have successfully removed rubber from their PFS pavement by the use of a high-pressure water (HPW) removal technique (Reference 16). Rubber deposits can be satisfactorily removed from PFS surfaces assuming they are properly constructed and not previously damaged (Reference 11). When rubber buildup is a problem, regular removal is a necessity to maintain adequate performance and ease of continued rubber removal (Reference 11). Damage to PFS during rubber removal has been known to occur. One reason for damage is an inadequate bond between the PFS and the pavement base (Reference 17).

EFFECT OF ENVIRONMENT, CONSTRUCTION, MAINTENANCE, AND DESIGN

A study of PFS, based on a very harsh winter in the Rocky Mountain region, proved that maintenance requirements are not excessive for PFS even in severe climates (Reference 18). On the other extreme, very high temperatures have caused some rutting and shoving problems (Reference 15). Cracking and raveling that occurred seemed to be from overlaying PFS on a poor pavement base structure, placement during unfavorable ambient temperatures, or permitting traffic access too soon after construction. PFS cannot prevent reflective cracking when used over structurally unsound existing pavement.

Attempts to seal cracks in PFS have been made. Some materials used are joint sealing compounds, sand asphalt mixtures, and precoated aggregates. The former two joint sealing methods will fill in the PFS voids and force the water to flow over the treated cracks. Use of precoated aggregate of about the same gradation as in the existing PFS appears to be a successful solution. Sealants have been successfully used on transverse joint cracks, but the sealant dams up the PFS when applied to cracks perpendicular to the direction of flow (Reference 11). Some attempts have been made to use asphalt seal coats for PFS maintenance. These attempts resulted in decreased internal drainage which worsened with increased seal coat applications.

Water in properly constructed PFS during freeze-thaw cycles in cold climates appears to have no serious adverse affects (Reference 18). PFS may aid in the removal of patch ice through the convection of warm air under the ice. However, when not properly constructed, a problem with PFS in some severe climates has been the formation of small circular blisters on the pavement surface caused by the development of ice lenses. During snow removal operations, the small areas affected by the blisters were scraped off. On one particular runway, water from the subbase was forced up through the cracks and joints in the underlying pavement. Blisters resulted from this water, which was trapped between the pavement and the PFS overlay (Reference 11). Degradation of the underlying pavement, caused by water penetration, can occur if an inadequate seal coat exists between the PFS overlay and pavement base. An inadequate bond between the PFS and base can also result in delamination.

Damage from jet exhaust blast has only been a problem on military airbases where the inclined exhaust blast of military aircraft strikes the pavement, or the afterburners are activated before rollout (Reference 17). Burning of PFS from exhaust blast can cause severe raveling (surface breakup due to loss of interaggregate bond) when aircraft remain standing with engines at a high thrust level (Reference 11).

With respect to the mix design of PFS, permeability is sensitive to changes in asphalt content, aggregate gradation, asphalt penetration grade, and percent voids in finished pavement (Reference 18). These variables in PFS mix design all affect the percent of pavement voids. Asphalt content should be chosen to obtain maximum stability and also minimize asphalt-filled voids. The aggregate should be of very high quality to prevent fracture or aggregate fatigue with resulting asphalt bleeding and void content loss. Too high a percentage of fine aggregates causes bleeding which can plug the PFS voids as shown in Figure 3 (Reference 19). This plugging of PFS has occurred in highway applications with a combination of very hot climates and high traffic volumes (Reference 12). High-penetration grade asphalts are more prone to bleeding and stripping under heavy traffic volumes and high temperatures. Figure 4 shows the affects of aggregate size and void content on permeability.

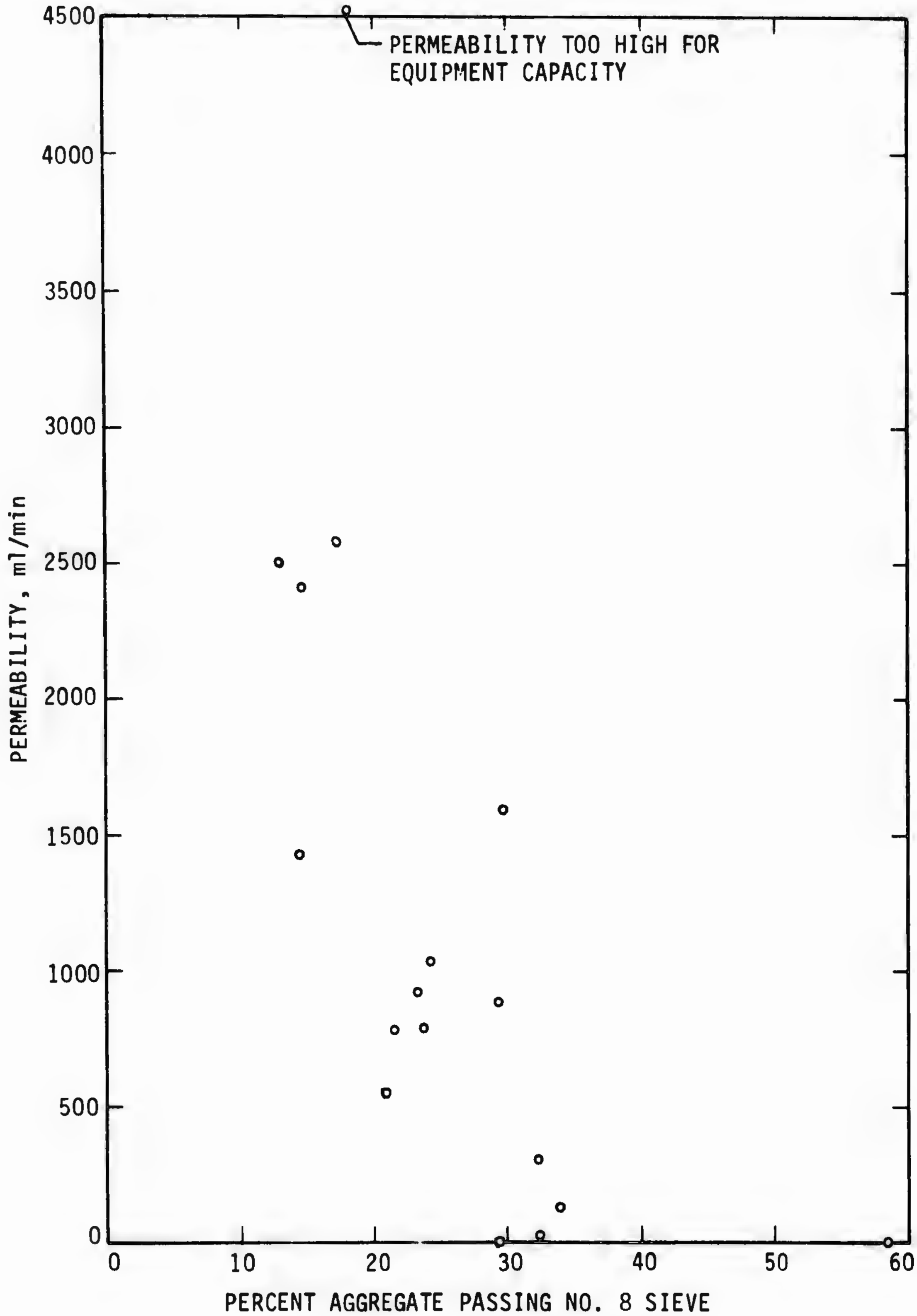


FIGURE 3. POROUS FRICTION SURFACE PERMEABILITY VERSUS PERCENT AGGREGATE PASSING NO. 8 SIEVE (REFERENCE 19)

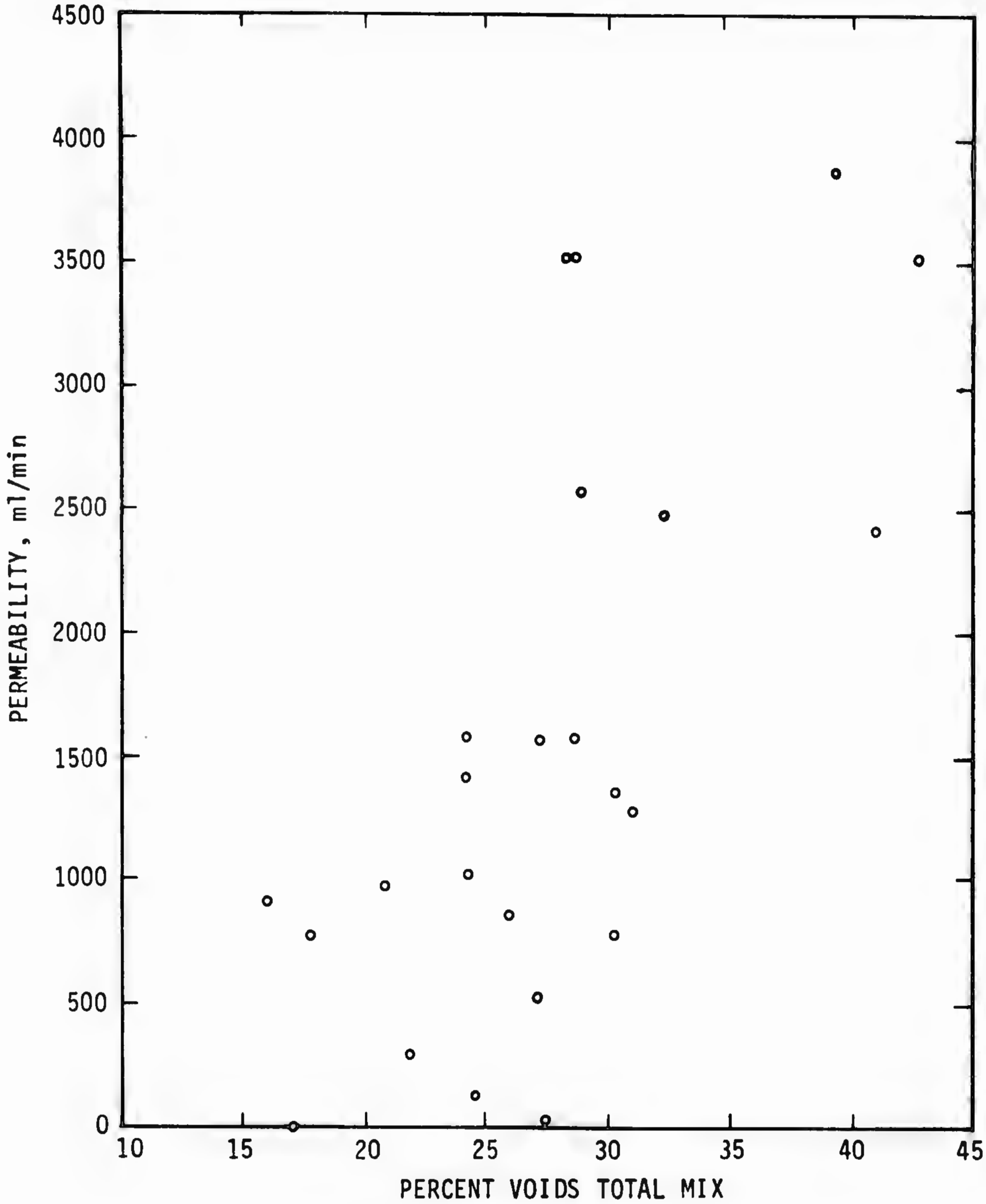


FIGURE 4. POROUS FRICTION SURFACE PERMEABILITY VERSUS PERCENT VOIDS IN TOTAL MIX (REFERENCE 19)

Pavement permeability is a function of the percent voids in the mix. According to White (Reference 19), the percent voids should be about 30 percent in airport PFS pavement. Permeability testing is recommended by White to verify proper PFS drainage.

Factors influencing the permeability of pavement (Reference 20) during construction and through its design life for highway applications are:

1. Segregation of mix during placement.
2. Temperature of mix during rolling.
3. Weight of roller.
4. Tire or contact pressure of roller.
5. Ambient temperature during mix placement.
6. Void content of the compacted mix.
7. Amount of traffic before winter rains.

The Texas Transportation Institute (Reference 13) identified, through highway experience with Open-Graded Asphalt Friction Courses (OGAFC), several variables ranked in descending order according to their effect on PFS. Table 1 lists variables affecting the drainage capacity of PFS. The variables listed in Table 2 influence its structural stability and durability.

COMPACTION DUE TO REPEATED WHEEL LOADINGS

One of the most important physical factors of PFS with respect to pavement friction is permeability. Volumetric flow rate in milliliters per minute and velocity units in feet per day are used to express permeability in the studies cited. Velocity is found by determining the drop in head over time. Volumetric flow is determined by measuring the drainage of water into the pavement over time. The minimum desired permeability for PFS is about 1000 ml/min (34 oz/min). This minimum figure was adopted by WES after evaluation of permeability tests, using WES equipment over a 3-year period on U.S. Airfield PFS pavement (Reference 17). A permeability study (Reference 11) on 13 PFS runways, including 6 British military bases, 5 European military bases, 1 U.S. military base, and 1 U.S. commercial airport showed that 9 of the runways had less permeability in the interior sections than in the edge sections. The remaining four runways had higher permeability measurements in the interior. Comparing the pavement edge and the touchdown zone, eleven sections had lower permeability in the touchdown zone, one edge section had lower permeability, and one touchdown section was not tested. The results of this permeability study are tabulated in Table 3.

These data indicate some compaction in the interior zone of the runway caused by aircraft traffic. On some runways lower permeability values may have been caused from overcompaction during the placement of PFS. Permeability values in touchdown sections reflect rubber buildup, overcompaction during construction, and compaction due to the aircraft traffic (Reference 11).

TABLE 1. INPUT VARIABLES INFLUENCING INTERNAL DRAINAGE CAPACITY OF OPEN-GRADED ASPHALT FRICTION COURSES (REFERENCE 13)

Importance Rank	Input Variable	Factors of Variable	Drainage Influence by
1	Pavement Cross Slope	Pavement Geometric Design	Hydraulic Gradient
2	Aggregate Geometric Characteristics	Top Size, Gradation, Particle Shape, and Surface Texture	VMA (Voids in Mineral Aggregate); Compacted Layer Permeability
3	OGAFC Mix Design	Proportions of Asphalt and Aggregate	Void Content of Compacted Mix; Compacted Layer Permeability
4	Condition of Pavement Surface before Application of OGAFC	Flushing-Bleeding on Pavement Surface	Decrease in Void Content of Compacted Mix by Filling with Excess Asphalt
5	Construction Procedures	Mixing, Placing, and Rolling Techniques	Void Content of Compacted Mix

TABLE 2. INPUT VARIABLES INFLUENCING STRUCTURAL BEHAVIOR AND DURABILITY OF OPEN-GRADED ASPHALT FRICTION COURSES (REFERENCE 13)

Importance Rank	Input Variable	Factors of Variable	Failure or Performance Mode Most Influenced
1	Type and Design of Underlying Pavement	Flexible Pavement-Characteristics and Thicknesses of Subgrade, Base, and Surface Courses	Rutting, Corrugations, Cracking
		Portland Cement Concrete (PCC) Pavement--Subgrade and Base Characteristics; PCC Slab Thickness	Cracking (Especially Reflection Cracks at Joints)
2	Condition of Pavement Surface before Application of OGAFC	Roughness, Porosity, Cracking, Flushing, Stripping	Rutting, Raveling, Flushing, Corrugations, Stripping
3	Treatment of Pavement Surface before Application of OGAFC	Overlay Type and Thickness; Use of Reinforcing Fabric; Prime, Tack, or Seal Asphalt Coating	Raveling, Flushing, Cracking
4	Construction Procedures	Mixing and Placing Temperatures; Mixing, Placing and Rolling Techniques	Pavement Roughness, Raveling, Rutting, Corrugations
5	OGAFC Mix Design	Proportions of Asphalt and Aggregate	Raveling, Flushing, Rutting, Corrugations
6	Asphalt Properties	Viscosity; Viscosity-Temperature Slope; Weather Resistance	Raveling, flushing, Rutting, Corrugations
7	Aggregate Type	Petrology; Microtexture; Strength and Durability; Surface Chemistry	Polish and Wear (Skid Resistance), Raveling, Flushing
8	Aggregate Geometric Characteristics	Top Size; Gradation; Particle Shape and Surface Texture	Pavement Roughness, Raveling, Flushing

TABLE 3. POROUS FRICTION SURFACE FIELD SAMPLES LABORATORY PERMEABILITY[a] (REFERENCE 11)

Base	Touchdown	Interior	Edge
RAF[b] Alconbury	1235	2225	3095
RAF Bentwaters	1260	1740	1670
RAF Lakenheath	350	1430	1130
RAF Mildenhall	460	1100	1860
RAF Upper Heyford	1715	3590	4170
RAF Woodbridge	3520	1610	3350
Bitburg Airbase	670	1410	1600
Hahn Airbase	160	125	290
Ramstein Airbase	85	1090	575
Spangdahlen Airbase	380	630	860
Wiesbaden Airbase	NT[c]	175	65
Hill Air Force Base	0	0	200
Stapleton International Airport	0	50	725

[a]Permeability in millimeters per minute through a cross-sectional area of 2026.8 mm^2 (3.14 $in.^2$).

[b]Royal Air Force

[c]Not Tested

A related study (Reference 18) of three U.S. military bases and seven U.S. commercial airports with PFS runways revealed a similar trend. Sections in and out of traffic areas measured for permeability showed less permeability in the traffic sections. The data from this study are shown in Table 4. These data suggest that the relationship between the British Pendulum Number and PFS permeability is inconclusive. The British Pendulum Number seems to be a better indicator of microtexture and polish rather than bulk water drainage.

Permeability of PFS and compaction under highway loading conditions have also been evaluated. In one study (Reference 21), a circular test track was used to evaluate six open-graded bituminous aggregate mixtures (OGBAM). These base courses were loaded repeatedly and tested for permeability. The base courses were rated according to the following requirements:

1. Adequate capacity to drain the pavement rapidly and retention of this capacity for some realistic service life.

2. Resistance to plugging.

3. Possession of sufficient stability so that the behavior of the drainage system itself does not interfere structurally with the behavior and the performance of the overall paving system.

The OGBAM tested were essentially PFS with an average void content of 29.1 percent, which is comparable to a PFS overlay. The OGBAM were tested on 76 mm (3 inches) of prepared subbase and the OGBAM were considered as base drainage layers for PCC pavement. The OGBAM had an average thickness of 102 mm (4 inches), which is greater than the approximately 25 mm (1 inch) of PFS normally used for an overlay. In comparison, the drainage properties of OGBAM and PFS appear to be similar. The coefficient of permeability for the two gradations of OGBAM used was estimated at 3.5 cm/s (10,000 ft/day). This coefficient was determined by flooding the pavement with a constant head of water and measuring the flow of water through the pavement into a collection basin. It was concluded, after loading the six OGBAM pavements with up to 246,000 load applications, that satisfactory performance can be obtained using OGBAM pavements.

In a study of highway applications of PFS (Reference 13), pavement permeability was shown to be influenced by the thickness of the OGAFC (Table 5). The OGAFC was shown to have less permeability and quickly became impermeable under traffic when constructed about 12.7 mm (0.5 inch) thick. A 19- to 25-mm (0.75- to 1-inch)-thick layer of OGAFC is shown to have much greater permeability throughout its life. The skid number (SN) and dynamic hydroplaning potential as a function of rainfall intensity are also compared with permeability in Table 5.

TABLE 4. 1974 POROUS FRICTION SURFACE (PFS) EVALUATION (REFERENCE 19)

Site No.	Location	Traffic Area	Flow Rate for Falling Head Permeability, ml/min	Average Skid Resistance, BPN[a]	
				Dry	Wet
1	Pease AFB	In	476	94	60
		Out	2031	94	72
2	Hot Springs	In	3000	94	72
		Out	4800	95	74
3	Nashville	In	108	94	52
		Out	1403	88	73
4	NAS, Dallas	In	3216		68
		Out	3675	95	66
5	Kirtland AFB[b]				
	Test Section 1	Out	363	87	63
	Test Section 2	Out	1265	83	67
	Test Section 3	Out	67	84	63
	Test Section 4	Out	33	81	67
	Test Section 5	Out	373	82	66
	Test Section 6	Out	0	83	62
	Test Section 7	Out	[f]---	82	68
	Test Section 8	Out	[c]---	80	63
6	Great Falls	In	1354	95	76
		Out	2058	98	83
7	Stapleton	In	67	98	62
		Out	718	94	74
8	Bartlesville	In	1539	95	67
		Out	1452	96	67
9	Salt Lake City	In	641	[d]---	61
		Out	3027	[d]---	65
10	Greensboro[e]	In	[f]---	[f]---	[f]---
		Out	4824	90	63

[a]The BPN [British Portable (Tester) Number] represents the frictional property of the PFS as determined using ASTM E 303-69.
[b]Due to the limited amount of traffic applied to the test sections, it was assumed that the results were indicative of an out-of-traffic area.
[c]Permeability was too high to measure.
[d]Surface was too wet to measure dry BPN.
[e]Newly constructed pavement.
[f]Data not available.

TABLE 5. INFLUENCE OF LAYER THICKNESS ON DRAINAGE AND SKID RESISTANCE OF OPEN-GRADED ASPHALT FRICTION COURSES (REFERENCE 13)

Point in OGAFC Life Cycle	Layer Thickness 0.75 to 1 in.	Layer Thickness ~0.5 in.
As constructed	High permeability. Good drainage. Low probability of dynamic hydroplaning if [a]$I < 0.5$ in./h. Good macrotexture; high speed SN depends on aggregate used.	Low permeability. Fair drainage. Low hydroplaning if $I < 0.05$ in./h. Good macrotexture; high speed SN depends on aggregate used.
At life-cycle mid-point (total traffic 15-20 x 10^6 vehicles per lane)	Medium permeability. Fair drainage. Low probability of dynamic hydroplaning if I = 0.1 to 0.2 in./h. Good macrotexture; high speed SN depends on aggregate used.	Impermeable. No drainage. Dynamic hydroplaning resistance depends on drainage through surface macrotexture. Original macrotexture preserved so that high speed SN depends on aggregate used.
At life-cycle end-point (total traffic 30-40 x 10^6 vehicles per lane)	Low permeability. Low to fair drainage. Low probability of dynamic hydroplaning if $I < 0.05$ in./h. Good macrotexture; high speed SN depends on aggregate used.	Impermeable. No drainage. Dynamic hydroplaning resistance equal to chip seal surface with same macrotexture. Macrotexture and high speed SN depend on aggregate used.

[a]Intensity of rainfall

PAVEMENT PERFORMANCE

A PFS applied to highway surfaces has been shown to lose permeability after about 1 to 2 years of service (Reference 22). This loss was shown to be caused from compaction under traffic and clogging by debris. For highway surfaces, PFS is suitable (because of retained surface texture) as a wet-weather skid-resistant surface, even when permeability is lost. In contrast, a similar study (Reference 13) indicated that PFS retained permeability throughout the life cycle with average daily traffic (ADT) of up to 20,700 vehicles. This study concluded that the life expectancy for a properly constructed PFS pavement appeared to be a minimum of 35 million vehicles per lane, or about 7 years. A factor which will limit life expectancy is the tendency of the asphalt binder to harden. The porosity of PFS leaves it open to atmospheric exposure, which can lead to oxidation and asphalt hardening. Figure 5 shows the susceptibility of PFS to hardening; if the asphalt cement becomes too hard in service, cracking and raveling of the surface layer may occur. Figure 5 illustrates an increase in wet weather safety performance of pavement due to the greater drainage capacity of open graded (PFS) pavement compared to dense graded pavement.

The stopping distance of highway traffic on wet PFS has been shown to be favorable (Table 6). The performance of PFS compared to dense-graded asphalt shows a 271 percent reduction in stopping distance for vehicles on wet non-flooded PFS.

With respect to airbase pavements, an evaluation by the British Department of Environment, after 8 months of extensive airbase operations at RAF Mildenhall, concluded that useful PFS service life should be at least 10 years (Reference 15). During construction, three variables affecting performance and appearance of PFS were gradation, bitumen content, and mixing temperature or viscosity. PFS can be constructed with confidence where good construction quality control procedures carefully monitor these variables (Reference 11). If a few precautions are taken--primarily correct maintenance procedures--PFS will exhibit excellent performance and durability under aircraft traffic, even when subjected to severe climatic conditions (Reference 17).

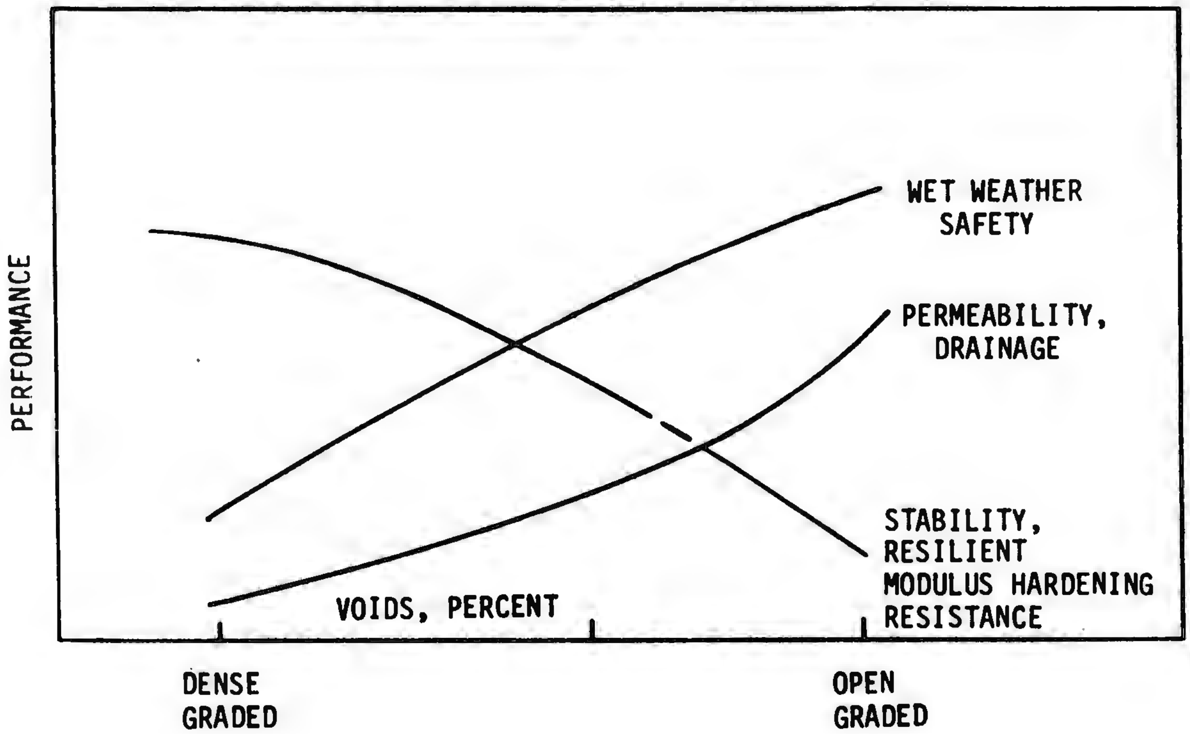


FIGURE 5. PERFORMANCE OF COMPACTED BITUMINOUS MIXTURES AS INFLUENCED BY THEIR POROSITY (REFERENCE 13)

TABLE 6. STOPPING DISTANCES FOR DENSE-GRADED AND OPEN-GRADED ASPHALT FRICTION COURSES[a] (REFERENCE 13)

Pavement	Pavement Condition	Vehicle Speed, mph	Estimated Level Road Braking Distance, ft
Dense-Graded	Dry	55	126
OGAFC	Dry	55	126
Dense-Graded	Wet; 0.09-inch water depth	55	720
OGAFC	Wet but not flooded	55	194

[a]Tire--ASTM E 501 0.34-in. tread, 24 lb/in.^{2}

SECTION V
PERMEABILITY TESTING DEVICES

Permeability equipment is used to indicate pavement drainage characteristics. Pavements with better drainage capability and permeability tend to have better frictional properties. While the evaluation of permeability is an index indicative of the friction level of a pavement surface, its usefulness as a frictional predictive tool is poor. Permeability equipment proves useful as a construction quality control device, and as a measure of decreasing permeability (infering decreasing friction levels) during a pavements life. The latter is useful for maintenance purposes.

Permeability devices studied in the literature were of two types, static and dynamic. Static permeability tests measure pavement permeability accurately up to the hydrodynamic pressure range which has been shown to occur at a vehicle speed of about 64 km/h (40 mph) (Reference 23). Dynamic permeability tests are an attempt to measure permeability in the hydrodynamic pressure range. The devices surveyed used either air or water as the fluid for the test procedure. The majority of the devices use static test methods. Some requirements for ideal static flow conditions (Reference 24) are:

1. Continuity of flow with no volume change during a test.
2. Flow with the voids fully saturated.
3. Steady-state flow with no changes in pressure gradient.
4. Direct proportionality of velocity to flow with pressure gradients below certain values, at which turbulent flow starts (Laminar flow).

These conditions and also the following criteria were used to compare the devices surveyed:

1. Type of seal used at the equipment-pavement interface.
2. Comparison of the device to some standard.
3. Repeatability of the testing device data.
4. Ease of equipment use.
5. Portability for field use.

Two dynamic and four static permeability devices were considered for use on PFS (Table 7). Most of these devices, with appropriate adaptors, could be used either in the field or in the laboratory. The test devices are summarized according to advantages, disadvantages, and limitations in Table 8. These devices are discussed in detail on the following pages.

DYNAMIC PERMEABILITY DEVICES

Two dynamic permeability devices were studied; one used water and the other air as fluids to determine pavement permeability. The dynamic water device (Reference 23) uses an explosively pressurized 16,129-mm^2 (25-$in.^2$) rectangular piston to force the piston, and the fluid beneath it, against the specimen surface (Figure 6). The resulting hydrodynamic pressure is similiar to the buildup of hydrodynamic pressures under an aircraft tire as tire hydroplaning speed is developed (References 6 and 23).

TABLE 7. REVIEW OF PERMEABILITY DEVICES CURRENTLY IN USE

Permeability Device	Test Principle	Test Mode		Fluid Used		Test Site	
		Dynamic	Static	Air	Water	Lab	Field
University of Kentucky (Reference 24)	Test consists of measuring the volume of water forced through pavement in unit time. Peak pressures up to 225 $lb/in.^2$.	X			X	V	V
Pennsylvania State University (Reference 26)	Test consists of measuring the flow rate of air released into the pavement by a compressed air tank. Pressures generated to about 100 $lb/in.^2$ minimum.	X		X		V	V
Pennsylvania State University (Reference 27)	Test consists of measuring the constant flow rate of air passing through pavement. A compressed air tank provides the constant air presure.		X	X		C	C
ASTM (Reference 23)	Test consists of measuring the air flow rate passing through pavement under a low negative constant pressure created by a falling head of water.		X	X		C	C
Birmingham University (Reference 31)	Test consists of measuring the time for a volume of water to pass through the pavement.		X		X	[a]---	V
WES (Reference 19)	Test consists of measuring the time for a head of water to fall from 10 inches to 5 inches while passing through the pavement.		X		X	C/V	C/V

V = Variable pressure gradient

C = Constant pressure gradient

[a]Not applicable for lab testing.

TABLE 8. ADVANTAGES, DISADVANTAGES AND LIMITATIONS

Permeability Device	Advantages	Disadvantages	Limitations
University of Kentucky	°Measures flow through pavement at hydrodynamic pressures	°Expensive equipment °Requires skilled operator °Tests in rapid succession causes data point scatter °Could damage sample	°For PFS some difficulty could be encountered keeping an adequate head of water on the pavement surface for operation of test
Pennsylvania State University (Dynamic)	°Measures flow through pavement at hydrodynamic pressures °No water required, sample condition unchanged	°Expensive equipment °Requires skilled operator °Compressible nature of air causes problems with test results	°May not work well on a highly porous surface such as PFS
Pennsylvania State University (Static)	°No water required °Easy to use °Direct flow readout °Fits in single suitcase	°Expensive equipment	°May not work well on a highly porous surfaces such as PFS
ASTM	°Inexpensive equipment	°Low output pressure °Requires skilled operator °Quantity of flow must be timed and then converted to a flow rate	°May not work well on a highly porous surfaces such as PFS
Birmingham University	°Interchangeable rubber rings of different hardness for surface contact	°Quantity of flow must be timed and then converted to a flow rate	°Must be adapted for use on grooved PFS
WES	°Easy to use °Inexpensive equipment	°Quantity of flow must be timed and then converted to a flow rate	°100 lb surcharge required on the device seal may cause compaction of the surface

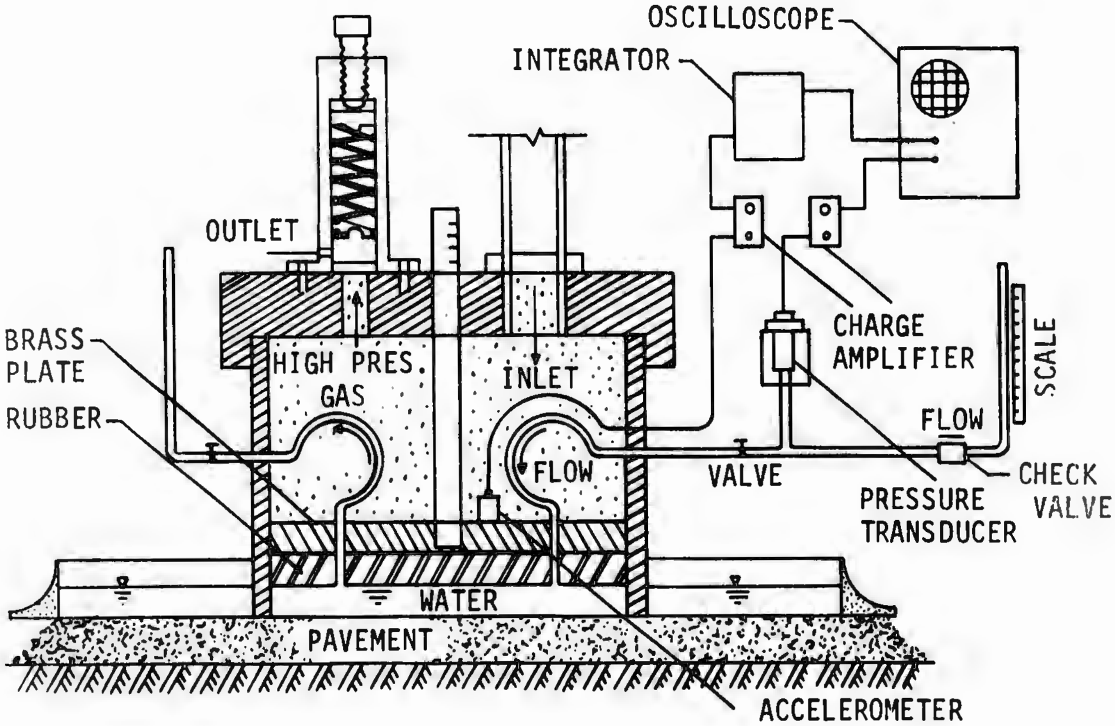


FIGURE 6. SCHEMATIC OF EXPLOSIVELY PRESSURIZED DEVICE USED TO MEASURE HYDRODYNAMIC CHARACTERISTICS OF PAVEMENT SURFACES (REFERENCE 23)

Pavement and specimen interface consists of water trapped to a specific depth by material placed on the pavement around the equipment perimeter. The dynamic device using water was tested by the University of Kentucky (Reference 23). The test results were compared to that of a Soiltest AP-400A static air meter (no longer manufactured). The comparison showed static test procedures only apply to measuring the potential of hydroplaning at speeds up to 64 km/h (40 mi/h). This device was field-tested and had good repeatability;* but tests in rapid succession caused a scatter in data points. Heating of the piston cylinder and buildup of burned gunpowder deposits were the controlling variables. It is thought that this device would be difficult to set up on PFS because the water required for pavement interface would be difficult to trap at sufficient depths for operation of the testing apparatus. This device has not been tested on airfield PFS. The dynamic blast of water into the sample could possibly damage the pavement. This device has been used for field and laboratory testing on highway pavements.

For dynamic air permeability testing, a device (Reference 26) was developed using a compressed air tank, a pressurized chamber with a pressure regulator, and ball valves. This equipment releases a blast of pressurized air from the discharge chamber into the pavement (Figures 7 and 8). The pressures generated were usually within the pressure range of 90 to 283 kPa (13 to 41 $lb/in.^2$), cited in Reference 6, which would be generated by highway vehicles. In contrast (Reference 6), hydrodynamic pressures generated using a Type VII aircraft tire were 0 to 1379 kPa (0 to 200 $lb/in.^2$). Therefore, this device may not be useful on airfield pavements where higher hydrodynamic pressures are exerted, which may exceed the equipment capacity.

Pavement to equipment interface is sealed with a commercially available sealant, applied in a 3.18-mm (0.125-inch)-diameter strand. The dynamic air permeability data plotted with static water permeability data had a correlation coefficient of $r = 0.803$. Good repeatability was shown in this comparison, but when dynamic air permeability data were plotted with static air permeability data, a less significant correlation was found. Because air is compressible, it is probably affected by two void types, continuous and occluded (stopped-up) voids. Static water permeability is affected only by continuous voids. The greater the percentage of occluded voids, the greater the variance could be in the comparison of data. The dynamic air permeability device appears to be easy to use and carry as a portable unit for field use.

STATIC PERMEABILITY DEVICES

Other equipment considered is of the static type. These devices should meet the ideal conditions stated earlier for static flow. Several types of devices were considered and all of the equipment was adapted or adaptable for field and laboratory use.

The Pennsylvania State University Static Air Permeability Meter (Reference 27) consists of three compressed air tanks, a double air regulator, an

*Personal Communication, J. W. Hutchinson

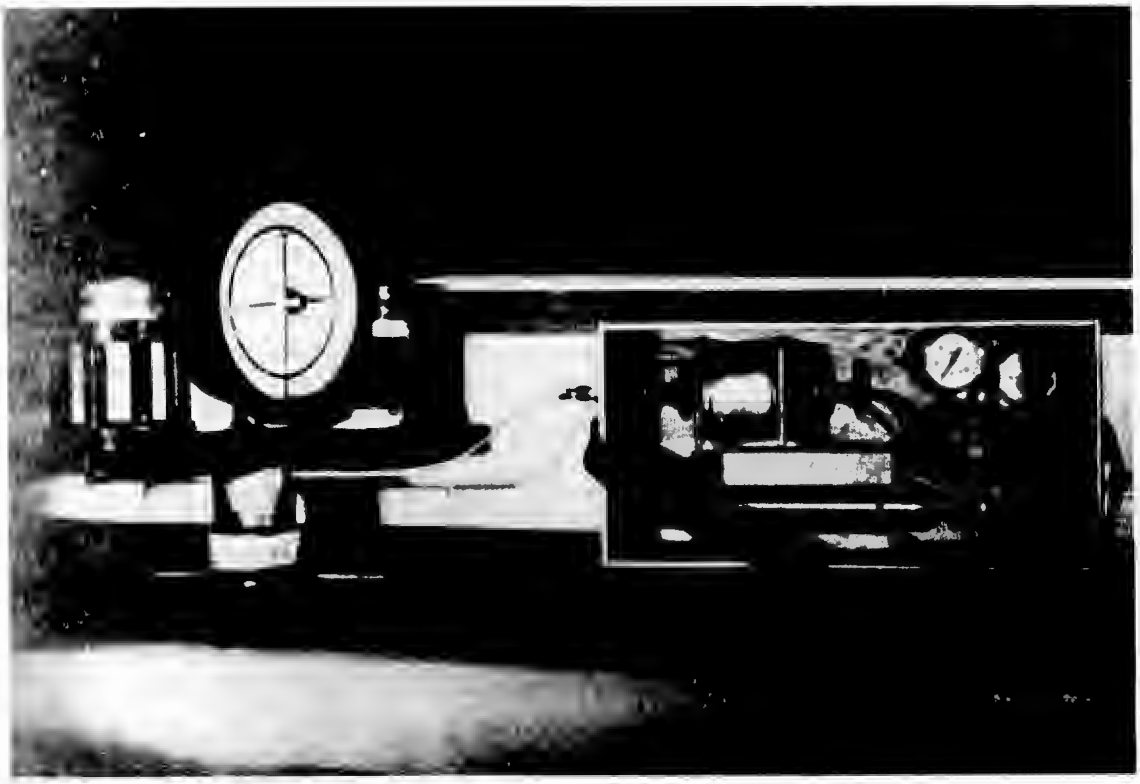


FIGURE 7. DYNAMIC AIR OUTFLOW METER
(REFERENCE 26)

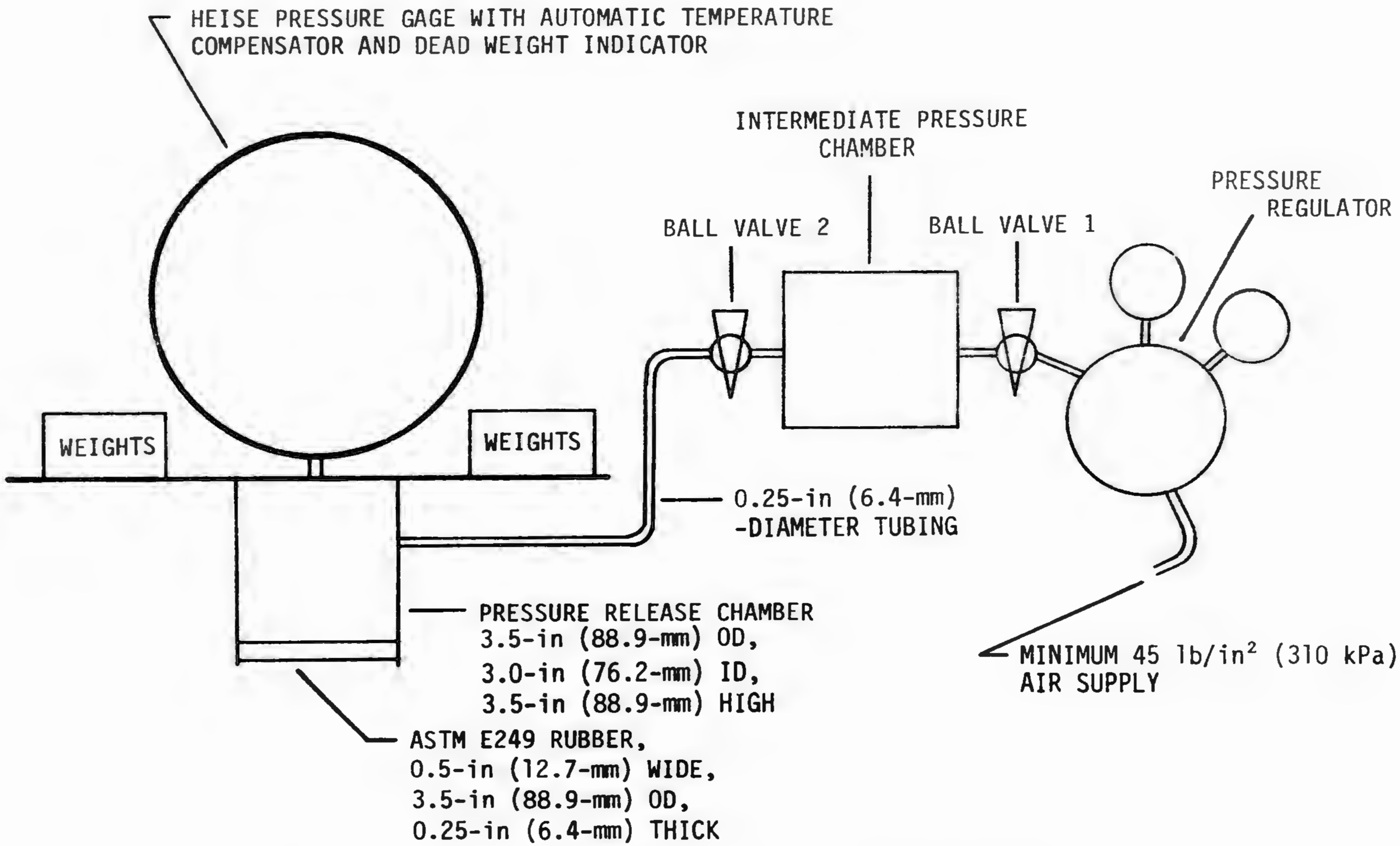


FIGURE 8. SCHEMATIC DIAGRAM OF DYNAMIC AIR OUTFLOW METER (REFERENCE 26)

air filter, on-off switch, three precision metering valves, five airflow meters, and a pressure gage. This device uses pressurized air input at a constant pressure to measure airflow rate through porous pavement (Figures 9 and 10). Static conditions for ideal flow are met by this device. A commercial sealant can be used for the pavement to equipment interface.

The static air permeability test data were plotted with static water permeability data and found to have a correlation of r = 0.918. The device has good repeatability and is easy to use. Measurements of permeability in 5 seconds with a variation in flow from 0.2 cm^3/day (0.012 $in.^3$/day) to more than 25,000 cm^3/minute (1526 $in.^3$/minute) are possible. Depending on the pavement permeability, about 1500 measurements can be taken without refilling the compressed air tanks. The device is compact enough to fit in a single suitcase (Figure 9).

The American Society for Testing and Materials (ASTM) Static Air Permeability Meter (Reference 24) measures the rate at which air can be forced (pressure system) or drawn (vacuum) at low pressures through bituminous pavements (Figure 11). At the pavement interface, a soft rubber ring is used to seal the device to the pavement. It can be used for four procedures, two laboratory and two field. Tests can be conducted using either the pressure or vacuum system. The equipment consists of four parts:

1. Pressure control device
2. Manometer
3. Field cell
4. Laboratory cell

This procedure may not meet the requirements for ideal flow because of the falling head used to develop air pressure. This method produces a constantly decreasing air pressure which should be compensated for to obtain accurate flow rates. A very similar device (Figure 12) developed by the California Research Corporation (subsidiary of Standard Oil Company of California) was field tested by Pennsylvania State University and was found to have some other disadvantages (References 27 and 28). At least 1 minute is required to obtain a quantity of flow, which must be timed and then converted to a flow rate. The device has a maximum air output of 305 mm (12 inches) of water pressure [about 3.5 kPa (0.5 $lb/in.^2$)]. The pressure at stopcock 3 (Figure 12) must be large enough to create a pressure at the pavement surface which can be detected at the manometer. As much as 552 kPa (80 $lb/in.^2$) pressure has been shown to be required. Therefore, this device is probably inappropriate on a highly porous surface such as PFS because of the low pressure generated.

No correlation between the results of this device to other permeability tests were made, but good correlations were shown using pavement core permeabilities compared to readings obtained from in-place pavements using this device (Reference 29). The repeatability of this device was shown to be reasonable in tests by the California Research Corporation. The ASTM Static Air Permeability Meter is portable for field or laboratory use.

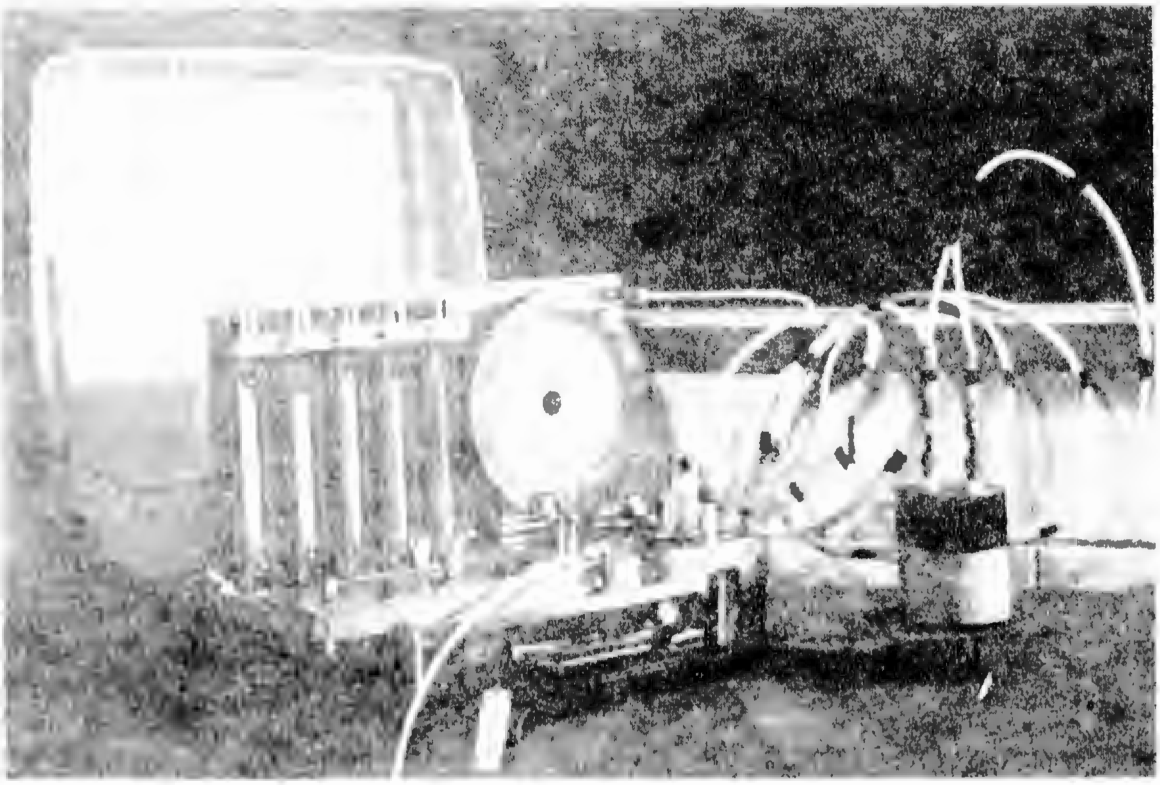


FIGURE 9. STATIC AIR PERMEABILITY METER
(REFERENCE 27)

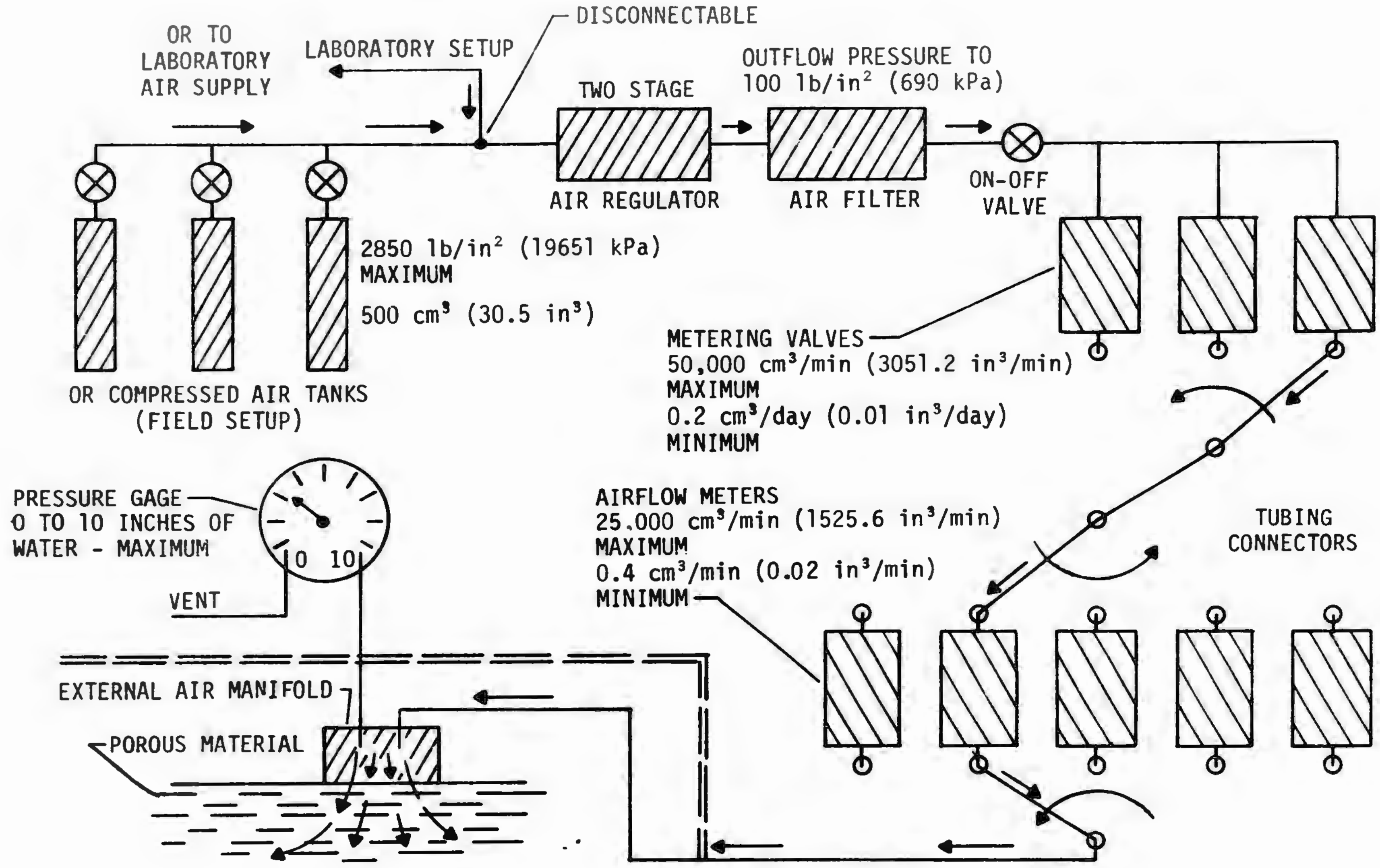


FIGURE 10. SCHEMATIC DIAGRAM OF STATIC AIR PERMEABILITY METER (REFERENCE 27)

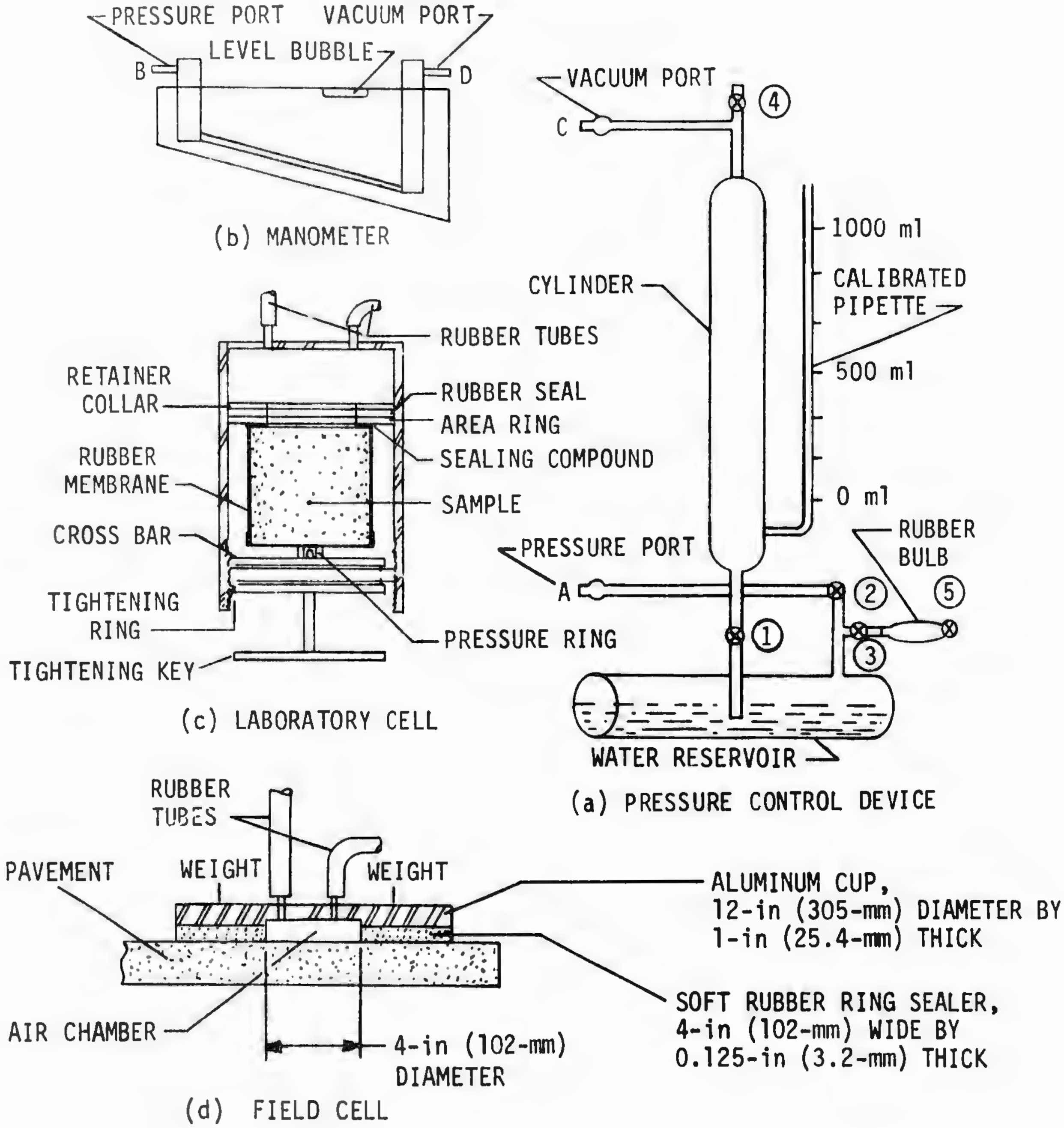


FIGURE 11. ASTM STATIC AIR PERMEABILITY METER (REFERENCE 24)

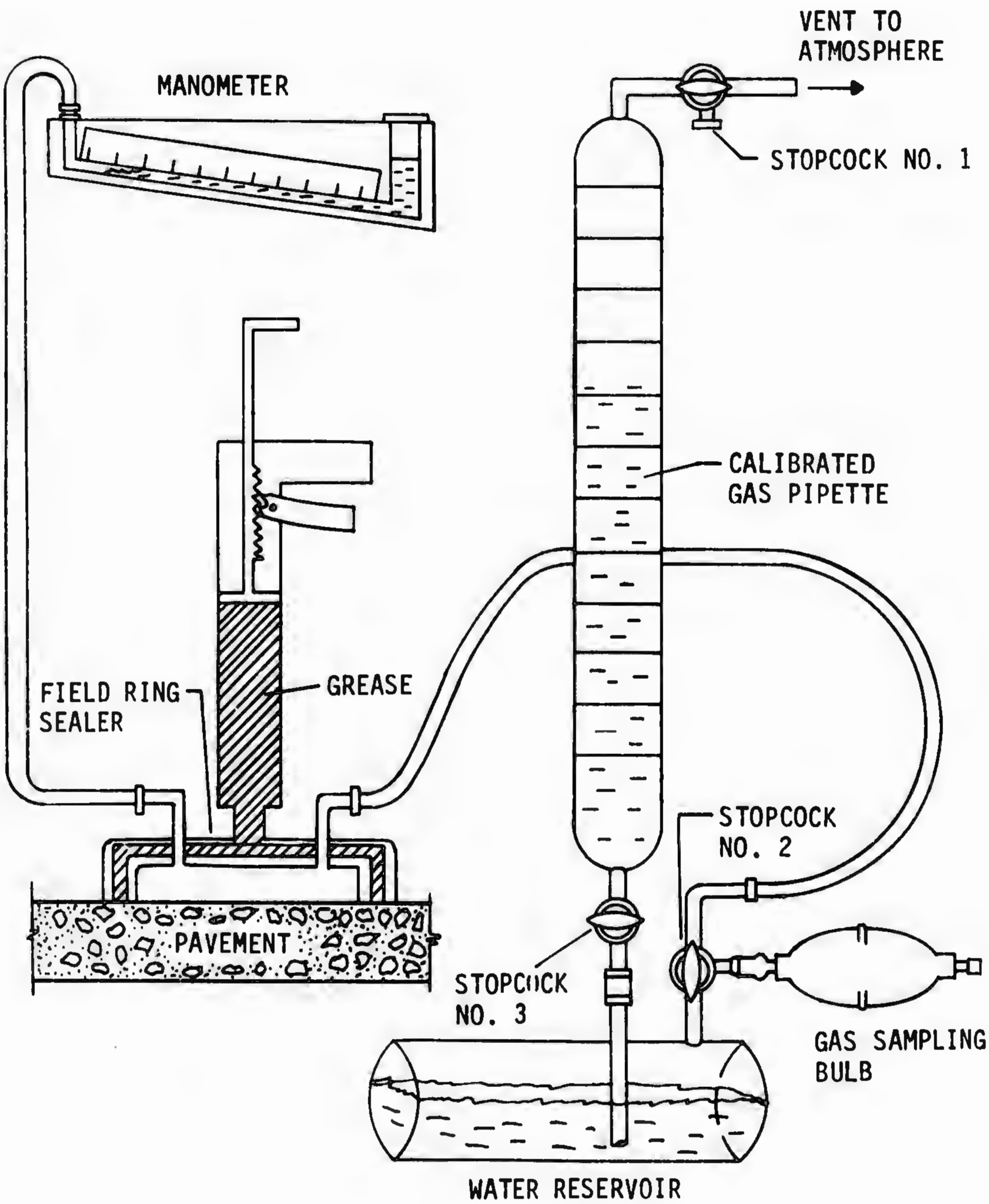


FIGURE 12. SCHEMATIC DIAGRAM OF CALIFORNIA RESEARCH CORPORATION STATIC AIR PERMEABILITY METER (REFERENCE 28)

Moore (Reference 7) experimented with an outflow water permeability meter to measure the surface drainage capacity of laboratory specimens. The outflow meter was modified in a later study by pressurizing the water cylinder and surcharging the equipment with air pressure (Reference 30). The modified outflow meter is better adapted to laboratory tests. Another modification of Moore's outflow meter was made by Birmingham University when the rubber sealring was thickened. This modification reduced leakage around the pavement-device interface to give more accurate permeability measurements on porous surfaces.

The Birmingham University outflow meter (Reference 31) consists of a transparent cylinder with a hole on the pavement contact end through which water outflow is controlled, a rubber ring, and a weight which is applied to the top of the device (Figures 13 and 14). This device uses a falling head to measure the combined flow of water through a test sample. The pavement-device interface uses a rubber ring, which is easily changed to permit different hardnesses of rubber to be used. Permeability measurements were repeatable but are not compared to other device measurements. This device was developed for portability and ease of use.

The Army Corps of Engineers Waterways Experiment Station (WES) developed a simple static water device (Reference 19). The equipment consists of a graduated transparent cylinder with an inflow valve, a rubber ring, and a load gage. This equipment can be used with constant head or falling head methods (Figures 15 and 16). When using the constant head method, permeability is measured as a flow rate. This flow rate is found by calibrating the scale of settings for the variable-flow pump used to maintain the constant head (Reference 32). The rubber ring is sealed between the device and pavement by an applied load from a vehicle. This device was not compared to any other type of permeability equipment test results as a control, but was shown to have good repeatability. The field device is portable and easy to use. The test procedure and details are included in Appendix A.

Other experience has shown better results on PFS when the rubber ring was replaced with a silicone-sponge rubber gasket to prevent surface flow and measure more representative permeability values (Reference 13).

Other pavement permeability test methods were found in the literature search. Another static air permeability testing device in use is the Air-Permeameter (Reference 33). This device is used for construction control of asphalt concrete (AC) pavement. The device is made of a 152-mm (6-inch)-diameter pipe, 203 mm (8 inches) in length, which is fitted with a low pressure gage and a check valve. A hand pump supplies 28-kPa (4-lb/in.^{2}) pressure which flows through a sample contained in the pipe. The time for the pressure to reduce to 3.4 kPa (1/2 lb/in.^{2}) is recorded. A simplified technique is used to measure static water permeability of pavement by forming a grease ring on the pavement surface and then applying water to the area within the ring. Permeability is determined by the rate of water flow into the pavement (References 20 and 22). While this method may be easy to use, separation of pavement permeability and evaporation rates is difficult, if not impractical.

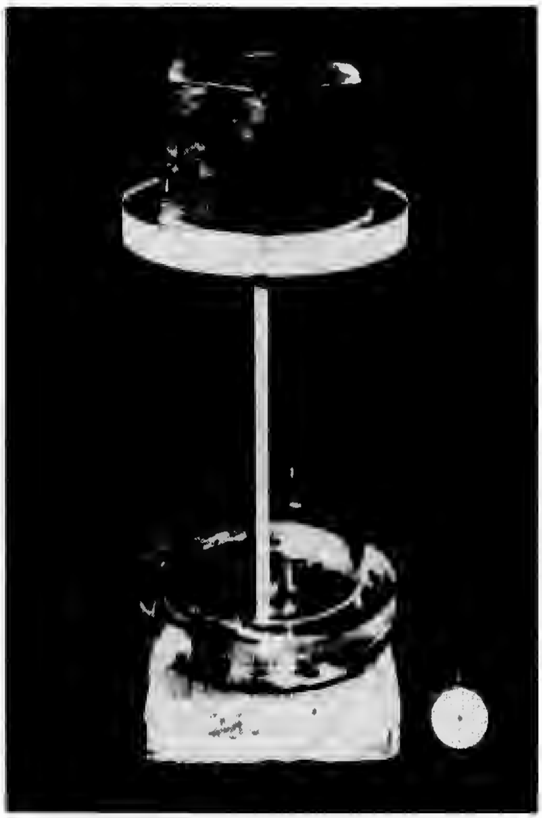


FIGURE 13. OUTFLOW METER
(REFERENCE 31)

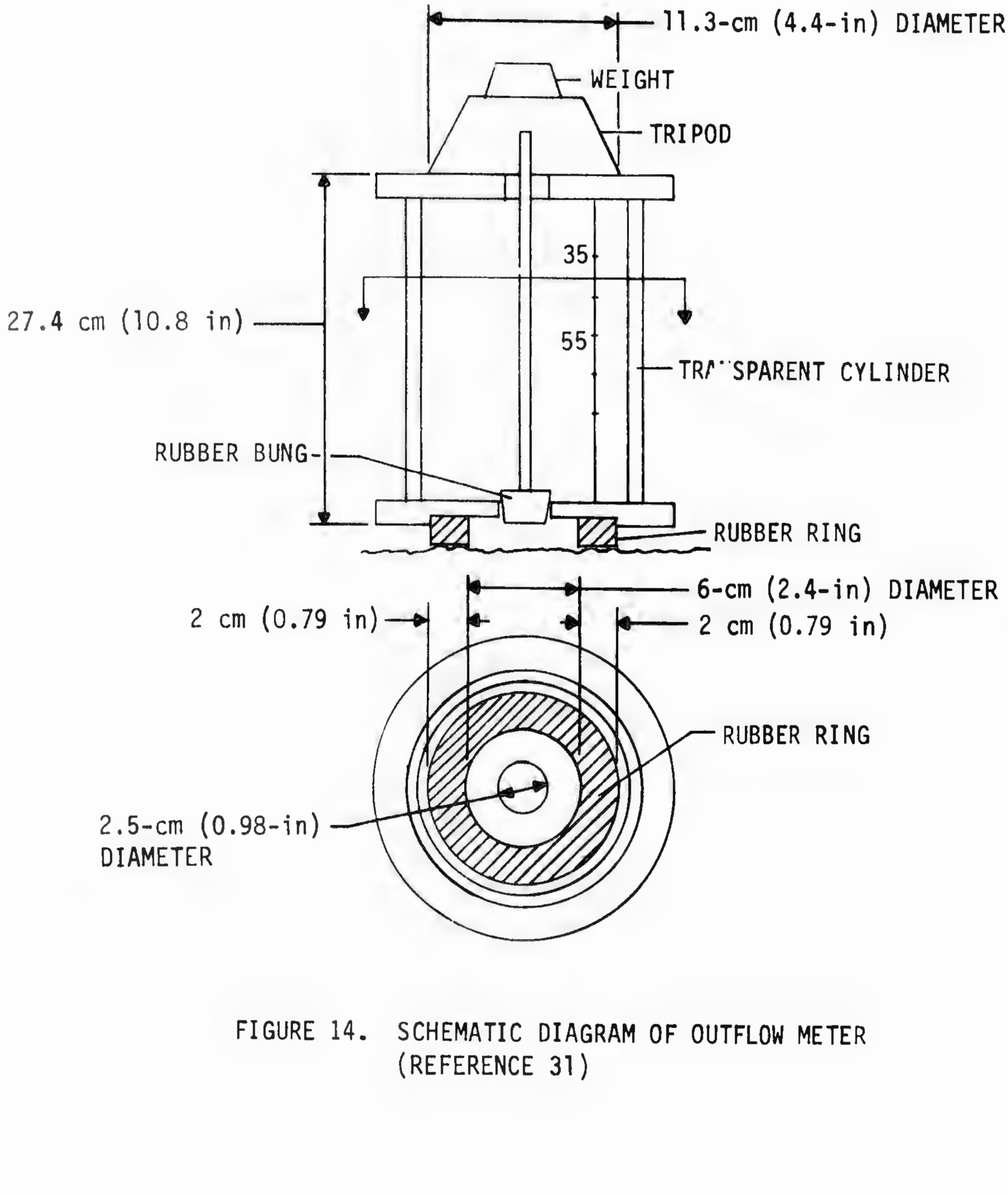


FIGURE 14. SCHEMATIC DIAGRAM OF OUTFLOW METER (REFERENCE 31)

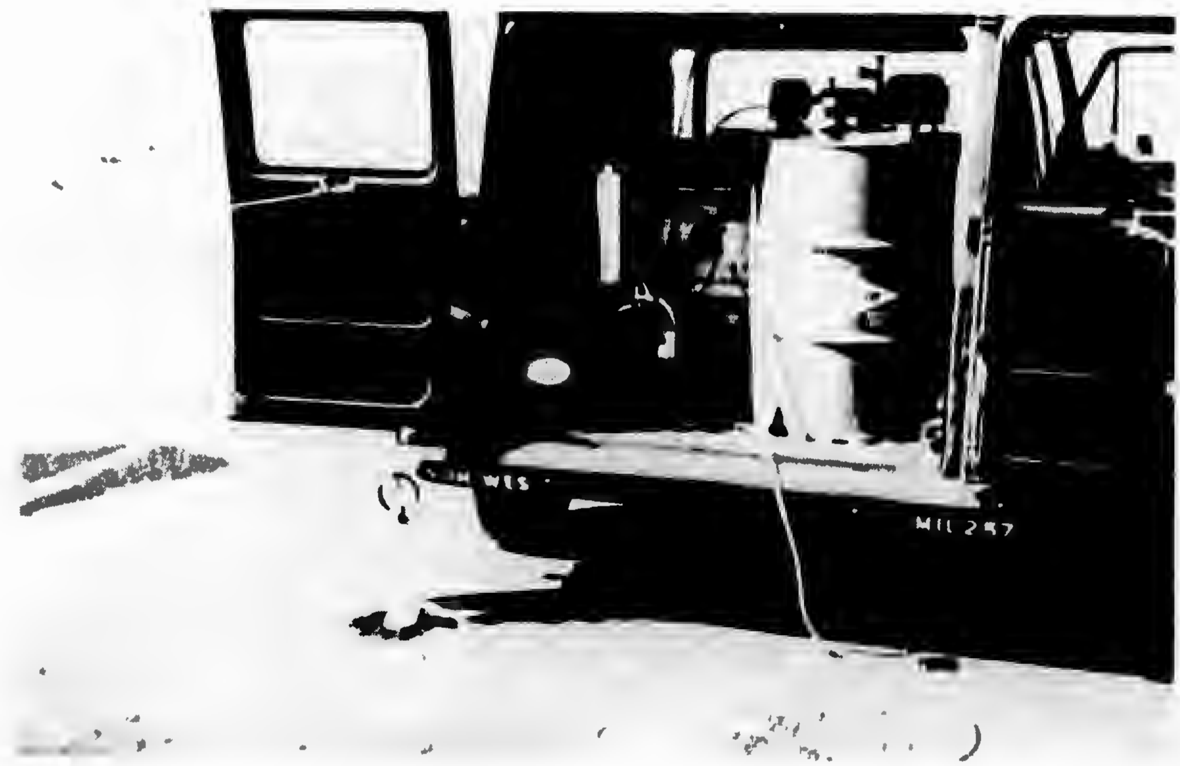


FIGURE 15. WES STATIC WATER PERMEABILITY DEVICE
(REFERENCE 19)

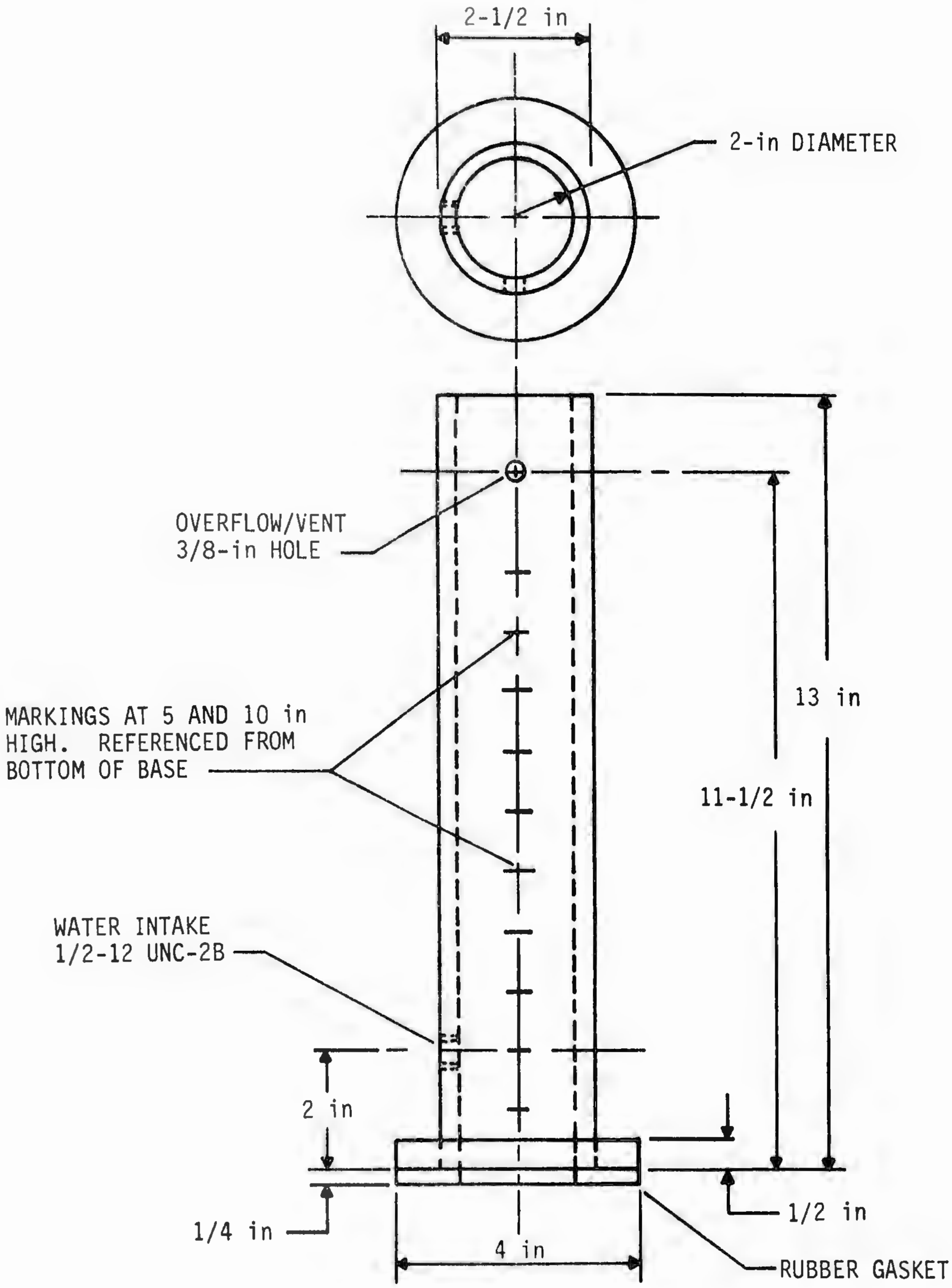


FIGURE 16. WES PERMEABILITY DEVICE (1 in = 25.4 mm)
(REFERENCE 19)

This simplified technique was investigated and tested by Gilbert and Keyser (Reference 25) along with five other methods which were selected from a group of fifteen permeability devices. Gilbert and Keyser concluded that a standard unit of permeability needs to be established and suggested that K/L (K = permeability, L = length of porous medium) be used. Permeability devices tested were of the static type and are very similar in operation to static devices presented in this report. Selection of the type of permeability meter according to the purpose of measurements, with respect to their inherent limitations, is shown to be important. Further studies were recommended to establish the precision of the different permeability devices tested.

Another device used to measure permeability is the RAE Surface Texture Test Rig shown in Figure 17 (Reference 34). This device is intended to measure the flow of water through the tire footprint-runway surface interface under pressure. Water is supplied from a fire engine through a measuring venturi to the center of an 11 inch diameter pad held down to the test surface by a beam, which in turn is held down by two heavy vehicles.

Of the permeability devices presented, only the WES Static Water Permeability Device has been used for evaluating airfield PFS pavements. The remaining devices have been tested on highway pavements. The dynamic devices modeling hydrodynamic pressures appear to have potential in measuring permeability experienced at high pressures by airfield PFS pavement. The use of pressurized air to measure PFS permeability may not work well considering the porosity and continuous voids commonly found in airfield PFS.

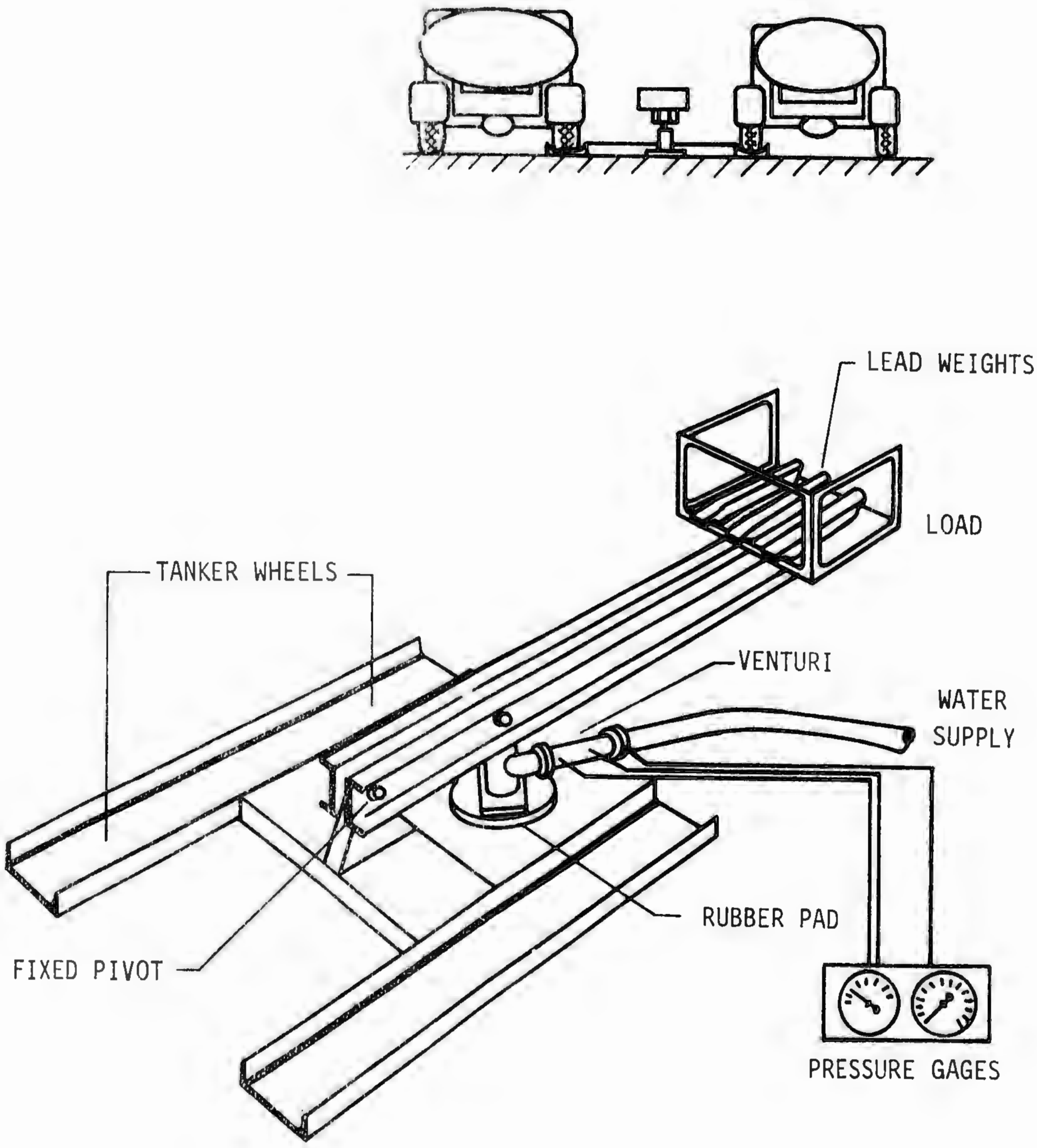


FIGURE 17. R.A.E. SURFACE TEXTURE TEST RIG
(REFERENCE 34)

SECTION VI
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

From the literature search, six permeability testing devices were selected as being the most representative. The devices include the following:

Dynamic

a. Dynamic Permeability Testing Device (water)

b. Dynamic Air Outflow Meter (air)

Static

a. Static Air Permeability Meter (air)

b. ASTM Air Permeability Meter (air)

c. Outflow Meter (water)

d. Static Water Permeability Device (water)

Permeability tests have been recommended by WES to measure drainage capacity of porous friction surfaces (Reference 19). The dynamic permeability devices considered in this report appear to be able to model the hydrodynamic pressures developed on the pavement surface during actual operating conditions. The use of the dynamic air permeability meter seems to be questionable because of the compressible nature of air. Furthermore, the dynamic water permeability device had some operational problems when performing tests in rapid succession. In addition, there is some question about the validity of dynamic test results because of the violation of Darcy's law in dynamic testing. Further work is needed to check the validity of test results and investigate techniques of dynamic permeability testing.

For static tests, the air permeability meter using pressurized air at a constant flow appears to be the most portable, easiest to use, and fastest measuring device. A direct readout of the flow rate is given by this equipment. This device, which takes about 5 seconds per reading, could minimize runway down time. Other devices that measure flow require time measurements by the operator. Cost of the air permeability meter is comparable to nuclear density equipment, which can cost about $2,500 to $5,000. However, tests of the air permeability meter have been performed on highway pavements only and leaves some question about the equipments ability to adequately measure typically very porous airfield PFS. Testing of the air permeability meter on airfield PFS is necessary to confirm the functional ability of the equipment on very porous surfaces.

Of the outflow style devices found in the literature search, only the WES device was shown to effectively measure airfield pavement permeability. A drawing of this device is shown in Figure 16 and the test procedure is discussed in Appendix A. The WES static water device testing procedure is more time consuming, but is probably less costly than the static air permeability meter. Permeability is very important in the functional operation of porous friction surfaces and can be accurately monitored using the WES static water device.

Problems have been experienced with dynamic testing devices, namely violation of Darcy's law and operational problems. The dynamic devices appear to have some future for measuring permeability of pavements at hydrodynamic pressures. The static water permeability meter used by WES has been shown to be effective on PFS. Static devices using air have been effectively used on highway pavements, but have not been tested on very porous pavements such as airfield PFS. Some further testing needs to be done with Static air devices on PFS.

RECOMMENDATIONS

The WES static water device has been shown to effectively measure the permeability of airfield PFS. Extensive field and laboratory testing by WES has shown the equipment to be reliable and easy to use. Fabrication costs of this equipment should be nominal. This test device and procedure are provided in Appendix A. This equipment could be used by an airbase or airport as a maintenance tool to measure PFS permeability.

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APPENDIX A
WES PERMEABILITY TEST DEVICE

The WES permeability test device consists of a clear plastic standpipe [2-inch (5.08 cm) ID and 2 1/2-inch (6.35 cm) OD] with a height of 13 inches (33 cm). The device has a 1/2-inch (12.7 mm) thick, 4-inch (10.16 cm) OD collar on the bottom with a 1/4-inch (6.35 mm) thick sponge-rubber gasket [2-inch (5.08 cm) ID and 4-inch (10.16 cm) OD] to prevent surface leakage (Figure A-1).

The results of the permeability tests are affected by the surcharge load applied to ensure contact of the standpipe and pavement surface. A surcharge load of 100 pounds (444.8 N) has been satisfactorily used to ensure that the condition of the tests are reasonably constant in this respect. Any method of supplying this surcharge is applicable, provided it is constant and is applied perpendicular to the pavement surface tested.

When the standpipe has been positioned and loaded, water is introduced into the standpipe to a level above the 10-inch (25.4 cm) mark on the side of the standpipe. The addition of water is then stopped, and the time to fall from the 10- to 5-inch (25.4 to 12.7 cm) level is measured with a stopwatch. This test is repeated three times and the average of the values is computed. The flow rate is determined from the relation $Q = VA$. Thus, for a 5-inch (12.7 cm) falling head, Q in ml/min is equal to 15,436.8 divided by the time to fall in seconds. A wide range in permeability measurements can be expected, but a reasonable lower limit of permeability for newly constructed PFC pavement is 1000 ml/min.

FIELD TESTS

In the field, an open truck door or bumper-mounted bracket can be used for the reaction weight, and an extension screw can be used to apply the load. The load system should include a ball bearing or universal mechanism for self-alignment. In the field where a truck is used to react against, the truck should not be parked broadside to the wind. Wind rocking the truck will cause the load to vary and affect the results.

LABORATORY TESTS

In the laboratory, good results have been obtained by conducting the test on 6-inch (15.24 cm) diameter specimens.

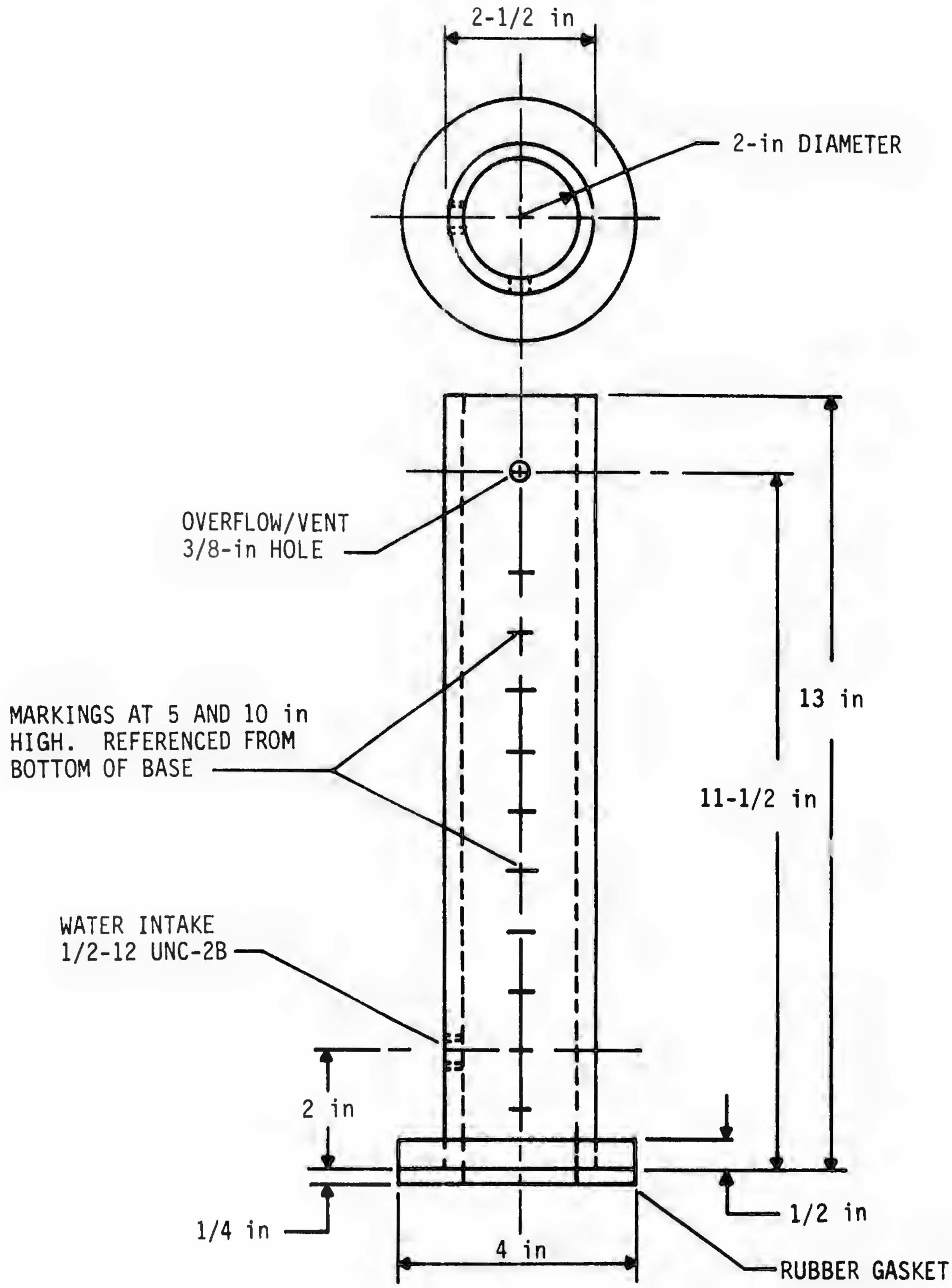

FIGURE A-1. WES PERMEABILITY DEVICE (1 in. = 25.4 mm).